IMPROVING FOOD SECURITY OF HIGHLY WEATHERED SOILS OF GÙRUÉ DISTRICT, MOZAMBIQUE

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Improving food security of highly weathered soils of Gùrué district, Mozambique.

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We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Master of Science in the Department of Tropical Plant and Soil Sciences, University of Hawai'i at Mānoa.

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General Abstract

Farmers among productive areas in Sub-Saharan Africa have been struggling to reduce food insecurity in tropical environments where they live. Low soil essential nutrients, low soil pH, acidic reddish – brown soils, high rainfall events coupled with pest attacks and diseases are some of the biotic and abiotic factors that challenge African farmers to improve crop productive, where Mozambique is not an exception. Locally available rock phosphate, limestone and common bean (*Phaseolus vulgaris L.,)* and pigeon pea *(Cajanus Cajan L.)* were tested in these acid reddish- brown soils of Mepuagiua at summit and backslope topographic positions. A Phosphate experiment using Evate rock phosphate and pigeon pea crop and limestone experiment using common bean crop was used in the research. The purpose of the experiment was to provide production alternatives to farmers by changing the soil conditions by applying and incorporating limestone; and the second, was to choose the crop (pigeon pea) to fit the soil conditions. A phosphate experiment was conducted to assess the feasibility of using local Evate rock phosphate (40.7% total P_2O_5) as a corrective to supply phosphorus. The rock phosphate was applied at rates of 20, 40, 80 and 160 kg total P ha^{-1}. For a comparison, triple super phosphate was also added at four P levels (0, 10, 20 and 40 kg P ha^{-1}). Factorial amounts of triple super phosphate (TSP) and Evate rock phosphate (ERP) were compared in terms of pigeon pea growth and grain yield. A limestone experiment, four rates of lime were applied,subsequently, 0, 1, 3, 6 Mg ha^{-1}. Urea (46%) as source of nitrogen and TSP (Triple superphosphate_45% P_2O_5) as source of phosphorus were applied 5 cm a part by hand at 20 kg.ha^{-1}; 208.6 g and 488.53 g respectively. A pigeon pea grain yield of 1000 kg grain ha^{-1} was possible with an application of 80 kg ha^{-1} of total P added as Evate rock phosphate. By comparison 20 kg P ha^{-1} as TSP was needed to reach a

maximum yield of pigeon pea grain. This ratio suggests that Evate rock phosphate was 25% as effective as TSP on a total P basis. This research suggests that the Evate rock phosphate can be an effective amendment that can enable or enhance food grain production on the acid, infertile upland soils of Central Mozambique. For common bean, soil pH was adjusted upward using lime from nearby Nampula Province. Germination and early growth were extremely limited with no lime application, however maximum growth occurred with the modest application of 1 Mg ha^{-1} of lime. Further studies are needed to determine how long the 1 Mg ha^{-1} of lime will continue to support improved common bean growth.

Chapter 1. Introduction

According to (FAO, 2009, p.1), food security is defined as when food availability meets people's dietary needs and preferences for an active and healthy life at all the times, and when people in a region have physical, social, and economic access to sufficient, safe and nutritious food. In Sub-Saharan Africa (SSA), though farmers have been fighting to maintain yields, food insecurity is high due to poor quality soils, land degradation, and low levels of fertilization coupled with declining soil fertility in the region. In addition, most African countries are severely affected by low crop production which leads to hunger, and several biophysical and policy constraints limit the ability of the country to meet global sustainable development goals (MDG Africa Steering Group, 2008; 1996; Sachs *et al.,* 2004).

A key strategy to improve food security by increasing local food production is through improved management of soil resources. In 1980s, physical fertilizer restriction removal to many African countries occurred was considered to be a major constraint to reduce food insecurity in the region (World Bank, 2008). Innovative farmers and medium commercial farmers in the region faced several constraints to the use expensive inorganic fertilizers for increasing crop yields and to finding better market price. In tropical acidic soils found in Africa, soil phosphorus concentration tends to limit crop yields due to its low concentration compared to the optimal level for sustainable crop production (Lompo *et al.,* 2009).

Therefore, researchers have suggested increasing the use of local deposits of rock phosphate, limestone and guano in Africa to alleviate phosphorus limitation and improve crop production (Bonzi *et al.,* 2011).

There is a need to conduct field and laboratory research using the locally, inexpensive mineral to assess its agricultural potential in order to help local famers to increase their crop yields and improve their livelihood.

1.1 Problem statement

African’s food insecurity is related to limited amount of soil phosphorus (P) available for plant growth, which is estimated to occur in two-thirds of the agricultural production areas (Batjes and Hinsinger, 2001). Moreover, depletion of soil fertility, weeds, pest attack and diseases were considered the major biophysical constraints to low food production per capita (Mugoma, 1996).

In Africa, agriculture is characterized by low inputs and produced by poor resource farmers (Maria and Yost, 2006). These conditions increase the vulnerability of crop production systems to biotic and abiotic factors such as drought, low soil nutrients, and pest and disease attack (Miklas *et al.* 2016). Losses of soil nutrient ranging from 30-60 kg ha^{-1} as NPK, shorter periods of fallowing and land pressure also have contributed to reduction of crop productivity (Nandwa, 2003 and Blackie, 1993). Essential soil nutrient levels and crop yields were reported by Mafongoya *et al. (*2006) to be the keys to reducing food insecurity in central part of Mozambique. On the crop aspect, Graham and Vance (2003) stated that regardless of the benefit of leguminous crops in the tropics its development has been slowed down due to factors such as high cost of agricultural inputs, inadequate market system as well as lack of information. Approximately 40% of common bean production in Africa is marketed, though it is mainly produced by female farmers to sustain their life, especially in Eastern and Southern of the continent (Wortmann *et al.,* 1999 and David *et al.,* 2000). According to Kumwenda, (1996), African farmers face constraints to build up and maintain soil fertility due to local adverse factors encountered by the majority of low income farmers. For example, in some areas, farmers do not have livestock due to presence of tsé-tsé fly. Consequently, animal traction is not used to plow the land and animal manures are not available as amendments to restore soil fertility. Mono-cropping systems practiced by the farmers increase the depletion of soil nutrients as well as food insecurity especially when fertilizers are not added to the soil.

Rusinamhodzi and Delve (2011) reported that, at the farm level, it is important that grain legumes provide multiple benefits in order to be acceptable to farmers. Farmers make their own evaluation which provides a basis for assessing the suitability of production options to their needs and local environment.

Farmers often understand the importance of the use of fertilizer and other modern inputs but the majority of farmers cannot use these modern inputs due to high purchase cost (Uaiene, 2006).

In addition, factors such as uncertainty of rainfall, pest and diseases discourage farmer investments in agriculture. We believe that farmers' adoption to modern inputs would increase, if the communication channels among rural development actors and farmers improve. For example, the majority of researchers in Uganda are able to write and speak with farmers using local language. This and other skills make the work efficient and precise when comes to deliver critical message or even provide recommendation and or suggestion. In contrast, few researchers in Mozambique speak farmers' local language thus a translator is always requested. Often times the message is not well delivered because the translator does not have agricultural background or even knowledge of the project goals.

1.2 Justification of the research

Because of its nutritional benefit and importance, common bean (*Phaseolus vulgaris* L.) provides proteins, vitamins and minerals essential for human diets across the world, especially in Africa *(*Broughton *et al.,*2003). Low levels of soil phosphorus (P) were reported among four targeted communities of the Legume Innovation Laboratory project (LIL project) in Mozambique namely, Tetete, Mepuagiua, Ruace and Lioma. In addition, the nutrient cations K^+, Ca^{+2}, and Mg^{+2} were present in soil at high levels as recognized by IIAM Mozambique (Maria and Yost, 2015). Scattered and locally available rock phosphate deposits (RPs) in Africa have been suggested as strategy to reduce food insecurity in the continent by alleviating soil P limitations. RP sources in other regions of Africa, such as Minjingu in northern Tanzania and Busumbu and Sukulu in Eastern Uganda, have been assessed and are used by farmers (Van Straaten 2002 and Bationo *et al.* 2006). The addition of RPs are particularly beneficial to crop production that relies on acidic soil with low soil Ca and P concentrations (Rajan *et al.* 1996 and Braun *et al.* 1997). In an early publication of this research, Rocha *et al.* (2017) observed that Evate rock phosphate in combination with the acid, reddish brown soils and the long crop cycle pigeon pea was an effective source of the often missing nutrient P for food grain production in Mozambique. In preparation for the phosphate research of this study, a sample of the Evate rock phosphate was collected and submitted to the International Fertilizer Development Center (IFDC) Laboratory in Alabama, USA, and the results are given in Table 1. They report that the Evate rock phosphate has an unusually high level of P (40.7% P_2O_5), however solubility is low (3.5 citric acid solubility and 0.95 neutral ammonium acetate solubility). These values are high in total P and low in solubility compared with data from Smallberger *et al.* (2010). There is a need for detailed investigation and characterization of the Evate rock phosphate deposits in north of Mozambique. Some papers point out that improper management of RP has potential negative effects on the environment (Funkey *et al.,* 2014).

Due to high costs of fertilizers, Mozambican farmers are rarely able to purchase modern inputs such as fertilizers, improved crop varieties, and pesticides for application in their fields. For example, water-soluble commercial P fertilizers such as triple superphosphate (TSP) and Super single phosphate (SSP).

Manhiça (1991) stated that the Evate deposit was discovered by the geophysical investigations for graphite by a Russian team in 1983. The Evate deposit was initially quantified at 155,413,000 tons of apatite ore with an average content of 9.32% P_2O_5. The analytical methodology used by the Russian Team was unknown, however. The Evate rock phosphate needs to be tested and evaluated in other phosphorus deficient soils using cereals and other type of crops to assess its agronomical potential for the country.

1.3 Overall research objectives

The overall objective of this research was to identify constraints on production, and opportunities for improving grain legume productivity in Mozambique through soil fertility management practices and crop selection.

1.4 Specific research Objectives

I. To evaluate a local source of phosphate nutrient to supply the P deficient soils.
II. To provide crop production alternatives on reddish–brown soils of Mepuagiua community at summit and backslope positions of soil catena;
III. To quantify the amount of lime necessary to remove soil acidity constraints and to increase plant growth.

Chapter 2. Literature Review

2.1 Agro- mineral deposits in the Sub-Saharan Africa

In sub-Saharan Africa, rock phosphate (RP) deposits of sedimentary and reactive qualities are present. Depending on RP origin, it differs mineralogical, textural, and in chemical characteristics. All these characteristics are generally influenced by the weathering processes occurring at soil surface level. High to medium-reactive (>15 g citrate-soluble P kg^{-1}) are usually the sedimentary RP deposits, while the igneous RP deposits are not good for direct application because it typically contains apatites of the fluorapatite [$Ca_{10}(PO_4)_6F_2$] and hydroxyapatite [$Ca_{10}(PO_4)_6OH_2$] varieties, or intermediate compositions. Therefore, these Igneous apatite varieties are relatively unreactive and not well suited for crop production (Stewart *et al*.,2005).

On the other hand, RP deposits, such as the Tilemsi in Mali, Tahoua in Niger and Minjingu in Tanzania, are sufficiently reactive for direct application (Sanchez *et al.,* 1997).

Factors such as low soil pH, low soil Ca levels, P-sorption capacity of the soil and cost differentials between RP and superphosphate, were listed by Sanchez and Salinas, (1981) to be the aspect to be considered when choosing P source. The soil and the superphosphate fertilizers function similarly in the soil. RP dissolves with the interaction of acids in the soil, thereby releasing soluble forms of P that are available for plant uptake. RP has been recognized as a valuable alternative source for P deficient soils, thus in order to enhance its dissolution, use of partially acidulating RP and reduce particle size by fine grinding are known as an option to the poor resources farmers (Babare *et al.,* 1997).

2.2 Mozambican rock phosphates and limestone deposits

Soil phosphorus (P) is a major limiting nutrient in tropical agriculture that is considered to be a global challenge because of finite P resources (Sattari, 2014). These irreplaceable and highly traded commodities have been extracted to sustain modern agriculture with the purpose of replenish nutrients that crop removes in the harvest (Steen, 1998). Only 25 % of SSA soils use fertilizer to produce food to feed African population, and when used, fertilizers are typically applied at the very low rates per hectare, regardless of low baseline soil nutrient concentration and low historical crop yields. In Mozambique, evidence of several of sedimentary Tertiary phosphate, small guano deposits, metamorphic, igneous and residual phosphates exist but are underexploited by the agriculture sector (IFDC, 2006).

According to Cilek and Manhiça (1991), Evate rock phosphate (ERP) containing approximately 14.5 million tons of P_2O_5 is the largest phosphate deposits in East-Central Africa and probably the largest metamorphic phosphate deposit located in Nampula province, Mozambique. In addition to that, they mentioned that limestone/dolomite should be tested for their agronomic efficacy as liming materials, particularly for these acid soils of Mozambique.

The two figures below show where these natural resources are located in Mozambique.

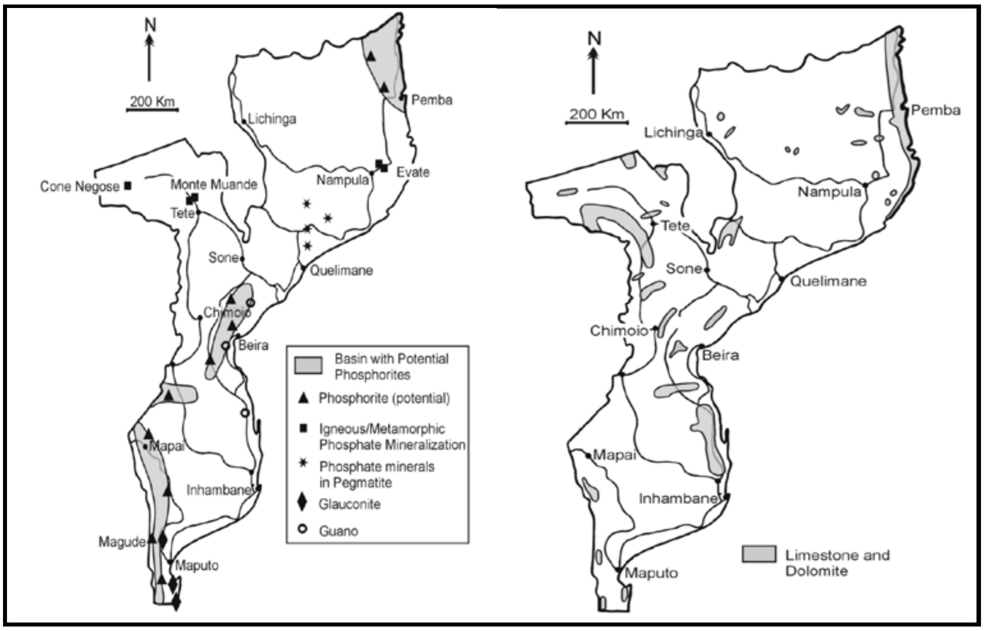


Figure 1. Location of rock phosphates and limestone in Mozambique (after Cilek 1989).

2.3 Factors affecting RP effectiveness and limestone

Many tropical soils have low P availability and high P-sorption capacity, hence application of low soluble P sources, such as RP, can be a useful strategy. Their use in traditional agriculture has an additional advantage because of monetary constraints with farmers. These low cost indigenous fertilizers are found in many tropical countries. The agronomic performance of RP depends on the reactivity of the material, defined by its magnitude and rate of dissolution. In contrast with fertilizers containing soluble P, is recommended that RP is applied to soils in fine particle form (ground to <150 µm diameter) Kanabo and Gilkes, (1988a) to increase the particle surface area exposed to soil factors that promote dissolution. This is because RPs are sparingly soluble in soil solution, maintaining very low equilibrium P concentrations, ranging from <1 μM P for the more reactive RPs to <0.01 μM P for the less reactive fluoroapatites at pH 6. The equilibrium P concentrations are very sensitive to pH, becoming 100-fold higher at pH 5 (Patterson *et al.*;1990). The mineralogy and chemical reactivity of the RP and the ability of the soil-plant system to modify soil solution pH become the major factors determining the rate and extent of RP dissolution and its potential agronomic effectiveness relative to soluble P fertilizers.

The presence of impurities, calcite, dolomite and gypsum in the RP is likely to reduce the effectiveness of the material as a P fertilizer (Mackay *et al.,* 1984; Howler and Woodruff, 1968), possibly due to an increase in pH and Ca.

Reactivity of RP is the combination physical and chemical properties that determines the rate of dissolution of the RP in a given soil under given field condition (Rajan *et al*., 1996). Poor soil nutrients like strongly nutrient depleted acid Oxisols and Ultisols, frequently occur in leached tropical soils. Soil acidity, Al toxicity and deficiencies of Ca and P are the characteristics of acid soils of the tropics. In order to overcome such agricultural constraints, processed rock phosphates (P- Fertilizers) are considered as potential alternatives to solve the problem.

Rock phosphate solubility in 2% formic and 2% citric acids are strongly related while solubility in formic acid and neutral ammonium acetate (NAC) are less so, particularly in the less reactive region of RP. Formic acid is the most convenient because allows easier characterization of reactive and less reactive rock phosphates. In addition, the formic acid test best predicts the agronomic effectiveness of a range of rock phosphate varying in their degree of substitution and particle size (Rajan *et al.,* 1992; Saggar *et al.,* 1993). RPs should be finely ground (<150 μm diameter) to increase their agronomic effectiveness relative to soluble P fertilizers (Rajan *et al.* 1992).

Initially, commercial fertilizers were designed for soils in the northern hemisphere but recently attention has been directed to the highly weathered, nutrient-poor and leached soils from the tropics. Such attention was recognized due the high phosphate sorption capacity caused by aluminum and iron oxide minerals (Leonardos *et al.,* 1987). The use of RP as an inexpensive inorganic as food production alternative and its agronomic effectiveness are influenced by several factors that below are described in section 2.3.1.

In general, factors affecting RP effectiveness can be classified in five categories: soil properties, chemical and physical properties of the RP source, plant factors and management factors.

2.3.1 Soil factors affecting agronomic effectiveness of rock phosphate

Dissolution of the RP and the sorption of the P resulting from the dissolved RP are two important mechanisms for the use of RP as a P source for crops. In addition to the chemical composition and particle size of the RP itself, mechanisms governing RP solubility are affected by soil properties. RP properties, soil properties, site factors, plant factors, and method and rate of application were considered by Singh and Lal, (2005) to influence the rate of dissolution of P from applied RP in the soil.

Direct methods for measuring dissolution of a RP in soil have invariably been based on the inorganic P fractionation procedure of Chang and Jackson (1957), or one of its many modifications. Thus, increases in iron-P and aluminum-P fractions in a soil to which a RP is added are considered to provide an estimate of P that has dissolved from the RP, whereas increases in Ca-P are considered to indicate unreacted RP (Cescas and Tyner, 1976).

Soil pH, CEC, Ca concentration, P concentration, P sorption capacity, and organic matter content are additional soil properties that influence the dissolution of apatite minerals in the phosphate rocks (Van Straaten 2002).

2.3.1.1 Soil properties affecting RP dissolution

Phosphate anions can be immobilized by cations such as Ca^{2+}, Mg^{2+}, Fe^{3+}, and Al^{3+}, converted to into less soluble compounds and become unavailable to the plants. This is one of the disadvantages of P fertilizer application (Zhang *et al.,* 1994; Davies *et al.,* 2002; Hinsinger, 2001). For example, the efficiency of P fertilizers is compromised due to fast reaction in calcareous soil. Calcium phosphate is formed with interaction of P fertilizer and Ca, thus become less available to the plants (Hedley and McLaughlin, 2005, Wang *et al.,* 2005).

The recovery of applied P is notoriously low. It has been estimated that in China, the recovery of phosphate fertilizer in the year applied is only 15%, and it is still less than 25% even when the residual effect is included (Li, 1999). The reaction of RP dissolution, Eq 1. and the reaction products listed are factors that affect RP dissolution: Soil acidity, Ca and P status define the direction and extent of the dissolution reaction.

$Ca_{10}(X)_2(PO_4)_6 + 12H^+$----------$10\ Ca^{2+} + 2\ X^- + 6\ H_2PO_4^{3-}$ (Eq. 1)

Where X can be F^-, OH^-, or Cl^-

From this equation, it is generally believed that acid soils favor the potential use of RP for direct application. The more acidic the soil is, the more rapid the dissolution rate of RP. The H^+ ions are a driving force for the dissolution of the carbonate apatite (Chien, 1977). Benefits from RP use as fertilizer can be obtained only generally if soil pH is lower than 5.5 (Diarra, 2004).

. Dissolution of North Carolina RP (Chien *et al.,* 1980) and Araxa RP from Brazil (Yost *et al.,* 1982) decreased with increasing of soil pH.

Sanchez *et al.* (1997) reported that in soils with pH values 6.2, similar agronomic effectiveness can be observed when superphosphates and highly reactive RP are used and compared. Chien *et al*. (1980) and Yost *et al.* (1982) observed that North Carolina RP and Araxa RP from Brazil dissolution decreases with increasing soil pH. Studies conducted by several authors report that soil pH condition (pH 6) in Alfisols and Ultisols was good measure of RP dissolution potential (Juo and Kang 1978) while in the same condition (Gilkes and Bolland, 1994; Diarra *et al.,* 2004) observed poor RP dissolution. These results suggest that the dissolution of RP in soil may not depend solely on the soil pH but also on the other soil properties. Equation 1. implies that the removal of the reaction product ions might enhance the solubility of the RP. Several studies have supported this conclusion. For example, Hammond *et al*. (1986a) added that the effective dissolution of RP in the soil not only requires low soil pH, but also low soil exchangeable Ca and low soil solution P concentrations.

In addition, Wright *et al.* (1992) observed a significant correlation between extent of RP dissolution and soil factors controlling exchanges in soil solution and P retention capacity of acid soils. Diarra *et al.* (2004) suggested that soil Ca higher than 30% reduced RP dissolution and RP in soil is influenced by the concentration of Ca and P in the solution (Mackay *et al.,*1986). Using 30 contrasting soils, Mackay *et al.* (1986) found that Ca- saturation, P – sorption capacity, and cation exchange capacity of the soil were three most important parameters influencing Sechura RP (from Peru) dissolution in soils. Sechura RP dissolution increased as exchangeable Ca decreased and as P- sorption capacity increased.

Wilson and Ellis (1984) found that an increase in the Ca^{2+} activity in solution at a constant pH resulted in a decrease in the rate of dissolution of RP. Many works have reported that increased soil P – sorption capacity increased RP dissolution (Smyth and Sanchez, 1982; Bolland and Barrow, 1988). A high soil P sorption capacity might enhance RP dissolution by reducing the concentration of P in solution around the RP particle (Smyth and Sanchez, 1982; Kirk and Nye, 1986). Loss mechanisms for RP particle for P and Ca, such as plant uptake and leaching, should encourage further dissolution of RP.

Khasawneh and Doll (1978) reported that soil organic matter is related to bonding of Ca and provides and effective sink for Ca by increasing the CEC.

Organic matter can also increase the soil water holding capacity and produces organic acids favorable for RP dissolution, both of which enhance dissolution of RP. Coarse-textured and sandy soils are not good sinks for P and Ca. Since the input amount greatly exceeds that taken up by plants, and a large amount of P accumulates in soil, studying its changes in soil and adopting adequate techniques to raise its use efficiency have become of great concern. In recent years, numerous agricultural scientists, including those specialized in soil science and plant nutrition, have concentrated on seeking new ways for reducing P fixation in soil and improving the recovery of P fertilizer in addition to transforming P that cannot be used by plants to become available for direct use by plants.

2.3.2 Rock phosphate properties

Briefly, rock phosphate can be a significant source of P for crops provided that soil pH is below 6.0, sufficient rainfall is available, and the solubility of the rock phosphate is high enough (Sinaj *et al.,* 2001). Rock phosphate dissolution also depends on chemical and physical properties of the RP source which vary widely among apatites in RP materials. The chemical properties reported in characterization studies of some West African RP carried out by Troung *et al.* (1978) include the solubility in neutral ammonium citrate, the CO_3/PO_4 ratio: the extent of carbonate substitution in the apatite structure and the surface area indicating potential reactivity. The most important property related to RP materials is their reactivity. Rock phosphate (RP) reactivity is dependent on isomorphic substitution within the apatite mineral crystal lattice (Easterwood *et al.,* 1989).

Smith and Lehr (1966) and Chien and Black (1976) observed that a carbonate molecule could not only replace a tetrahedral phosphate molecule in an apatite crystal but it would also weaken the crystal structure of the mineral. Therefore, increasing isomorphic substitution results in greater mineral solubility under acid conditions (Chien, 1977; Khasawneh and Doll, 1978; Hughes and Gilkes, 1986).

The citrate solubility of RP thus increases as the molar ratio of CO_3/PO_4 in the apatites increases. This agrees with the results reported by Leher and McCleallan (1972). The extent of RP dissolution was positively related to the citrate soluble P. In general, the RP with the highest specific surface area also has the highest citrate solubility. Because the RP dissolution process is a reaction that occurs at the surface of the RP particle (Barrow, 1990) the size of the RP particle (Joos and Black, 1950) and its porosity (Caro and Hill, 1956) affects its effectiveness. Experiments carried out by (Khasawheh and Doll, 1978; Joos and Black ,1950) have shown that rock phosphate agronomic effectiveness increases with a decrease in particle size. For example; corn yield was almost doubled when Baja California RP particle size was ground finer than 100 mesh (Escobar and Reyes,1994).

2.3.3 Plant factors affecting RP dissolution and P uptake

Plant factors include: (i) crop duration; (ii) the ability of the plant roots to take up the Ca or P in soil solution; (iii) the ability of plant to acidify the rhizosphere (legumes); and (iv) high root density. Xie, 1966 and Guo, (1981) found that is critical to apply P fertilizer to leguminous crops than the others because leguminous crops with a high N to P ratio in their tissue may promote, regulate nodule formation and absorb more soil P. As mentioned, Tao (1964b, 1983) used the ratio of N to P_2O_5 in crop tissue to indicate crop's responses to P fertilizer and concluded that when the ratio was higher than 3, crops would have good responses to P fertilizer (Tao, 1964a). Pushparajah *et al.* (1990) and Sales and Mokwunye, (1993) reported that that the agronomic effectiveness of RP can be equal or superior of soluble expensive fertilizer if it is used on long term crops acid tolerant crops, acid soils, such as oil palm and rubber. Plant P requirements tend to decrease in the following order: vegetable (annual) > long term > perennial crops. Thus, while RP may be a cost-effective way to supply P and sustain the often deficient nutrient P, it is also clear that soluble P is needed in many cropping systems and soils of West Africa. Examples include intensive vegetable production.

Direct application of rock phosphate is recommended for acid soils, though some plants acidify the rhizosphere by exuding malic and citric acids resulting in increased dissolution of RP particles (Kirk and Nye, 1986). For example, pigeon pea (*Cajanus Cajan*) was shown to be more efficient at utilizing iron bound phosphorus than several other crop species. The roots of legumes release piscidic acid that can complex iron to enhance the availability of iron-bound phosphorus (Ae *et al.,* 1990). Thus, the subsequent or intercropping of crops and trees with annual crops (Sales and Mokwenye, 1993) may benefit from the enhanced dissolution of the RP.

Deist *et al.* (1971) and Flach *et al.* (1987) suggested that high Ca uptake patterns of plants, like buckwheat (*Fagopyrum esculentum),* are responsible for improved responses of certain crops to applied RP. Growing plant roots can stimulate RP dissolution. Removal of the dissolved Ca and P from the zone of RP dissolution is considered to be the main reason for the increased dissolution.

2.3.4 Management factors affecting RP effectiveness

Rock phosphates tend to be more effective in soil conditions that support dissolution and when they are finely ground and broadcasted to maximize soil surface area in contact with soil. The presence of a Ca sink is probably the most important factor affecting the dissolution of RPs (Robinson and Syers, 1990), and they invariably compare poorly in terms of yield response to water-soluble products when applied to neutral and alkaline soils. The efficient use of fertilizers optimizes agronomic and environmental outcomes for farmers. However, compared to other major plant nutrients, P is poorly utilized by crops. The sorption of P by soils and the slow diffusion of orthophosphate ions in solution from the exchange complexes reduce the effectiveness of fertilizer applications. The efficiency of fertilizer P use is most conveniently calculated as the difference in P uptake, with and without P amendment, expressed as a proportion of the P applied. Typical values of apparent P recovery can range up to 30% depending on a number of site and fertilizer management factors, but it is most often reported to be <10% on soils well supplied with P (Greenwood *et al.,* 1980; Johnston and Poulton,1992; McKenzie *et al.,* 2003; Sharpley, 1986; Vanoverstraeten and Hanotiaux, 1996).

A study conducted by Enyong *et al. (*1999) observed that, farmers preferred compost fertilizers (Example: N-P-K-S-B) rather than available RPs in some parts of Africa.

2.3.4.1 Methods and rates of RP application

Banding is the placement of fertilizers in a continuous stream of material along the row of plants or under the plant, and is often proposed to be an efficient method of P application (Barber and Kovar, 1985; Kovar and Barber, 1987). Banding of P was shown to be superior to broadcasting for lettuce on the calcareous organic soils of the Everglades Agricultural Area in Florida (Sanchez *et al.,* 1990). Banding P near the seed generally results in more efficient uptake of P by the crop than a broadcast application at rates of <40 kg P ha^{-1}. Because of the low solubility of P minerals, P does not move rapidly in the soil and often only a short distance (Grant *et al.,* 2001). Therefore, fertilizer P applied may be available to succeeding crops for many years (Halvorson and Black, 1985a; Halvorson, 1989; Jose, 1981).

Barber (1984) pointed out that, in acid soils, application methods designed to increase the efficiency of P use should aim to reduce fertilizer-soil contact. The optimum volume of this zone appears to range from 1 to 24% of the total depth of cultivated soil and should be to the side of seedlings and seeds. An alternative technology to fertilizer placement is seed coating.

Scott *et al.* (1985) found that seed coats containing neutral P fertilizers such as reverted superphosphate and PAPR are effective in improving crop establishment. The degree of mixing of rock phosphate in the soil and the amount of RP that is applied have a major effect on RP dissolution. Broadcasting, as oppose to band application, exposes the RP particles to larger volumes of soil. Rock phosphates are the more effective when mixed with soil (Khasawneh and Doll, 1978).

Measurements of the dissolution of North Carolina RP in soil have shown a reduction in RP dissolution due to banding (Kanabo and Gilkes, 1988a). Several works have demonstrated that the proportion of RP that dissolves within the soil decreases with increasing level of RP application (Hughes and Gilkes, 1984). Yampracha *et al.* (2005) showed that the Kanchanaburi rock phosphate applied at 500 mg P kg^{-1} depressed RP dissolution. They observed that the high $CaCO_3$ content of the material was the main reason of that reduction in RP dissolution.

2.3.4.2 Timing of RP application

Phosphorus is less mobile compared to the other soil plant nutrient, therefore, the amount of this element to the plant are not adequate especially in soils of the tropics. For optimal timing of P fertilizer application, P applications can be done in advance of planting (Eghball and Gilley, 2001).

The dissolution of RP in these acid soils increases when it is applied before the crop planting. The slow release of P from RP favor an enhancement of residual effects of RP over time when compared to soluble P fertilizer (Sale and Mokwunye, 1993). However, Chien (2001) did not observe statistical differences in the effectiveness of North Carolina RP in low fixation capacity soils when either applied at planting or 6 weeks before planting.

Some studies done in Niger by Roesch and Picht (1985) in similar soils have shown that the residual effects of Tahoua RP on millet yield were greater than their effects in the first year of RP application and the duration of the effects depended on the rate of RP application. Similar results were obtained with Tilemsi RP (SAFGRAD, 1983).

The crop in the second and third year of RP application could benefit from residual effect of RP. These results suggest that the dissolution of the rock phosphate may have been the limiting factor rather than the sorption reactions. On the other hand, in acid soil the early application of RP reduced its effectiveness (Hammond *et al.,* 1986a), suggesting that high sorption capacity of acid soil be the dominant reaction.

2.3.4.3 Liming

Liming is known to negatively affect RP dissolution because it increases soil pH and exchangeable Ca and reduces exchangeable Al^{3+} concentration (Hanafi *et al.,* 1992).

2.3.4.4 Other Management factors

Several authors have shown that RP can be successfully used in alkaline soils with concurrent inoculation of P solubilizing microorganisms (PSM). Such microorganisms release P from RP rapidly increasing plant growth and P uptake (Kucey, 1989; Whitelaw, 2000).

Bar-Yosef *et al.* (1999) found that PSM produced acids, which react with the RP and released P into the solution. Several studies have demonstrated that arbuscular mycorrhizal fungi (AMF) improve plant growth and nutrient uptake by plants, particularly under low soil fertility conditions (Tinker, 1980).

One of the most dramatic effects of mycorrhizal infection on the host plant is the increase in P (Koide, 1991; Ortas *et al.,* 1996, Lambert *et al.,* 1979; Kothari *et al.,* 1991; Ortas *et al.,* 2001). AMF take up the same forms of P from the soil solution as roots do. There is no evidence of its availability of solubilize insoluble P (Pi) compounds (Bolan, 1991). The capacity of the mycorrhizal fungi to absorb phosphate from the soil and transfer it to the host roots (Asimi *et al.,*1980) is mainly explained by the ability of mycorrhizal hyphae to extend several cm from the root surface; whereas, roots of the host plant only can absorb P a few mm away from their surface. Thus, AMF enable roots to access a greater volume of soil (Hattingh *et al.,*1973; Mosse, 1981) for immobile nutrients such as phosphorus.

Besides all these management factors, the use of ammoniacal fertilizers could also acidify the rhizosphere and buildup the H^+ concentration in soil. Reaction involving H^+ is a driving force for RP dissolution to occur (Chien, 1977). Consequently, the use of ammoniacal fertilizers can enhance RP dissolution by acidifying the rhizosphere (Logan *et al.,* 2000).

2.3.5 Moisture content

In addition to all the factors mentioned above, moisture is required for the dissolution reaction to occur. In addition, soil moisture permits both diffusive and convective removal of reaction products from the site of dissolution of the rock phosphate, usually the surface. In this way, soil moisture helps to reduce the levels of Ca^{2+} and $H_2PO_4^-$ in the soil solution near the site of dissolution would strongly influence the dissolution of RP (Wright *et al.,* 1992).

Rock phosphate dissolution is inhibited when soil moisture decreases at field capacity (Kanabo and Gilkes, 1988b). Data from field studies in Senegal (Hammond *et al.,* 1986a) indicate that crop yield response to applied RP is linearly related to the mean annual rainfall between 500 mm and 1300 mm. High rates of leaching in sandy West African soils create environment for RP dissolution (Hanafi *et al.,* 1992). Direct application of RP is normally not recommended for low rainfall areas, due to erratic effectiveness under conditions of low soil water content (Hammond *et al.,* 1986a).

2.3.6 Mozambique agro-minerals information

Based on map developed by Manhiça (1989), Mozambique has limestone and RP deposits throughout the country, though under exploited. There are no studies conducted involving the exploration of rock phosphate's agricultural potential or even its physical and chemical analysis / content. Recent Evate rock phosphate analysis done by IFDC at Alabama shows that Evate rock phosphate has unusually high P content when compared to rest of African rock phosphate (high 40.7% of P_2O_5). Despite this high P content and low- medium solubity, there is huge gap in communication between the investigators and farmers. In our view, this is one of the factors that hamper agricultural development and reduction food insecurity among Mozambican communities. Evate rock phosphate could be potentially used to add P to these deficient soil nutrients to improve grain legume and cereal production in the country and limestone to reduce soil acidity as more crops can easily be grown in reddish brown soils in Gùrué district and in Mozambique.

Chapter 3. Comparison of Evate rock phosphate and triple super phosphate on pigeon pea yields at Mepuagiua community

3.1 Abstract

Acid, infertile reddish-brown soils characterize large amounts of central Mozambique. Few of these soils are in food production representing a missed opportunity for agricultural productivity and a missed alternative to improve the food security of the country. Low levels of soil nutrients such as calcium, phosphorus, and potassium limit crop growth. Local agricultural amendments for acid, infertile soils such as limestone and rock phosphate exist but are unexploited. An experiment was conducted to assess the feasibility of using local Evate rock phosphate (40.7% total P_2O_5) as a corrective to supply phosphorus. The rock phosphate was applied at rates of 20, 40, 80 and 160 kg total P ha^{-1}. For a comparison, triple super phosphate was also added at four P levels (0, 10, 20 and 40 kg P ha^{-1}). A long growth cycle crop of pigeon pea (*Cajanus Cajan* L., Mill sp. variety "ICAEP00020") with a growth cycle of 190 days was used to assess effectiveness of the local rock phosphate. A pigeon pea grain yield of 1000 kg grain ha^{-1} was possible with an application of 80 kg ha^{-1} of total P added as Evate rock phosphate. By comparison 20 kg P ha^{-1} as TSP was needed to reach a maximum yield of pigeon pea grain. This ratio suggests that Evate rock phosphate was 25% as effective as TSP on a total P basis. This research suggests that the Evate rock phosphate can be an effective amendment that can enable or enhance food grain production on the acid, infertile upland soils of Central Mozambique. Whether for direct application for acid-tolerant crops or acid soils or processed into soluble fertilizer phosphate, the existence of such a valuable resource provides a great opportunity for improved local food crop production.

3.2 Introduction

In Sub-Saharan Africa (SSA), phosphorus has long been identified as the major limiting nutrient in the vast majority of soils (Bationo *et al.,* 1997). Such soils constitute up to 55% of the agricultural land in SSA (Bationo *et al.,* 1986). SSA contains numerous rock phosphate deposits, and some are sufficiently reactive for direct application (Buresh *et al.,* 1997). Direct application of indigenous rock phosphates has been viewed as an attractive option for building soil phosphorus (P) fertility because it potentially involves lower production costs and capital investments than the production of water-soluble P fertilizers from indigenous rock phosphate sources (Hammond *et al.,* 1986; Rajan *et al.,* 1996).

Food security has been the focus of recent agricultural projects including the Legume Innovation Laboratory, which is conducting farmer decision-making regarding grain legume crops. A consistent limitation to food security has been the extremely low fertility and acidity of the highly weathered soils of the country (Maria and Yost, 2006). Recent studies indicate that such conditions are widespread in the central, potentially highly productive region Mozambique. Soil management of nutrient-poor acid soils has been highly successful in regions with acid soils (Fageria *et al.,* 2013) and multiple management alternatives are possible.

In Mozambique, fertilizers such as superphosphates are exceedingly expensive, of low quality, and seldom available in local markets. Recent research has explored the possible use of indigenous agro-minerals such as rock phosphates, as substitutes for expensive, imported fertilizers. According to Zavale *et al.* (2005), Mozambique can increase the production of all of crops by using its enormous potential of natural resources, improving agricultural infrastructure, and increasing household adoption of improved crop varieties and other new agricultural technologies.

Local food grain – pigeon pea

One of the crops of growing popularity among farmers in the acid soil region of Mozambique is pigeon pea (*Cajanus Cajan*, L., Millsp.) (ICRISAT, Malawi). The crop is moderately tolerant of the acid soil conditions characteristic of the region and also is well-known for drought resistance, in part due to deep rooting. This crop is tolerant of the acid soil conditions that are favorable for the reaction and dissolution of rock phosphates and it has a long duration growth cycle also favorable for the slowly dissolving rock phosphate. The locally preferred cultivars of pigeon pea range in maturity from 170 to 190 days (O. Madzonga, ICRISAT/Malawi, personal communication, 2016; C. Malita (IIAM/Nampula), personal communication, 2016). Tolerance to soil acidity by pigeon pea is not well characterized, but several researchers have documented that the plant roots exude organic acids that dissolve and solubilize otherwise insoluble phosphates (Otani *et al.,* 1996). These researchers report that pigeon pea exudes some 10-fold more malonic acid than do groundnut, cowpea or rice. Adugyamfi *et al.* (1990) report that pigeon pea tolerates low P conditions better than soybean. For these reasons, *Cajanus Cajan* may become a useful rotation crop in food production systems in this zone of Mozambique.

Local deposits of rock phosphate

Manhiça (1991) characterized Mozambican phosphate deposits as primarily deposits of apatite of two types: 1) Monte Muande-Monte Fema near Tete Province and 2) the Evate deposits in Nampula Province. The first was original crystalline limestones of Pre-Cambrian replaced and metasomatized together with injection of apatite-carbonate, apatite-magnetite, and apatite-silicate. The second was carbonatites with low contents of apatite dispersed or in hydrothermal veins. The Evate deposit was discovered by the geophysical investigations for graphite by a Russian team in 1983. The Evate deposit was initially quantified at 155,413,000 tons of apatite ore with an average content of 9.32% P_2O_5. The analytical methodology used by the Russian Team was unknown, however. In preparation for this research a sample of the Evate rock phosphate was submitted to the International Fertilizer Development Center (IFDC) Laboratory in Alabama, USA, and the results are given below in Table 1.

Table 1. Analytical results of Evate rock phosphate sample. International Fertilizer Development Center, Muscle Shoals, Alabama. Analyzed November 9, 2015.

Chemical	Results	Analyst	Method
Total P_2O_5, %	40.7	CSG	$HNO_3/HClO_4$- Molybdovanadate color method - visible spec
Citric Acid Sol. P_2O_5,%	3.75	CSG	SSSAP 1957 21 :183-188
Formic Acid Sol. P_2O_5,%	2.12	CSG	ZPDB 1953 62:262-264

NAC Sol. P_2O_5,% 1st ext.	1.46	CSG	AOAC - Molybdovanadate color method - visible spec
NAC Sol. P_2O_5,% 2nd ext.	0.95	CSG	AOAC - Molybdovanadate color method - visible spec
Cd, ppm	0.52	CSG	AFPC- HNO_3/HCL- ICP
Co, ppm	7	CSG	AFPC- HNO_3/HCL- ICP
Cr, ppm	9.8	CSG	AFPC- HNO_3/HCL- ICP
Cu, ppm	14	CSG	AFPC- HNO_3/HCL- ICP
Mn,%	0.1	CSG	AFPC- HNO_3/HCL- ICP
Mo, ppm	2.2	CSG	AFPC- HNO_3/HCL- ICP
Ni, ppm	4.7	CSG	AFPC- HNO_3/HCL- ICP
Pb, ppm	14	CSG	AFPC- HNO_3/HCL- ICP
Zn, ppm	22	CSG	AFPC- HNO_3/HCL- ICP

Yager (2014) reported that the corporation Vale S.A. of Brazil was engaged in a prefeasibility study on a new phosphate mine at the Evate deposit. Depending on the results of the study, predictions were that the mine could produce 2 million metric tons yr^{-1} of Evate phosphate rock.

3.3 Goals and Objectives

3.3.1 Goals

1. To improve food security at local and national levels in Mozambique.
2. To teach farmers about rock phosphate benefits and importance to sustainable crop production in the country.

3.3.2 Objectives

I. To assess the potential of using Evate rock phosphate of Mozambique to supply phosphorus to the acid soils in the Mepuagiua community.

II. To determine the amount Evate rock phosphate in comparison with triple super phosphate needed to achieve maximum yield and biomass of pigeon pea in a Mepuagiua community.

3.4 Materials and methods

3.4.1 Site description

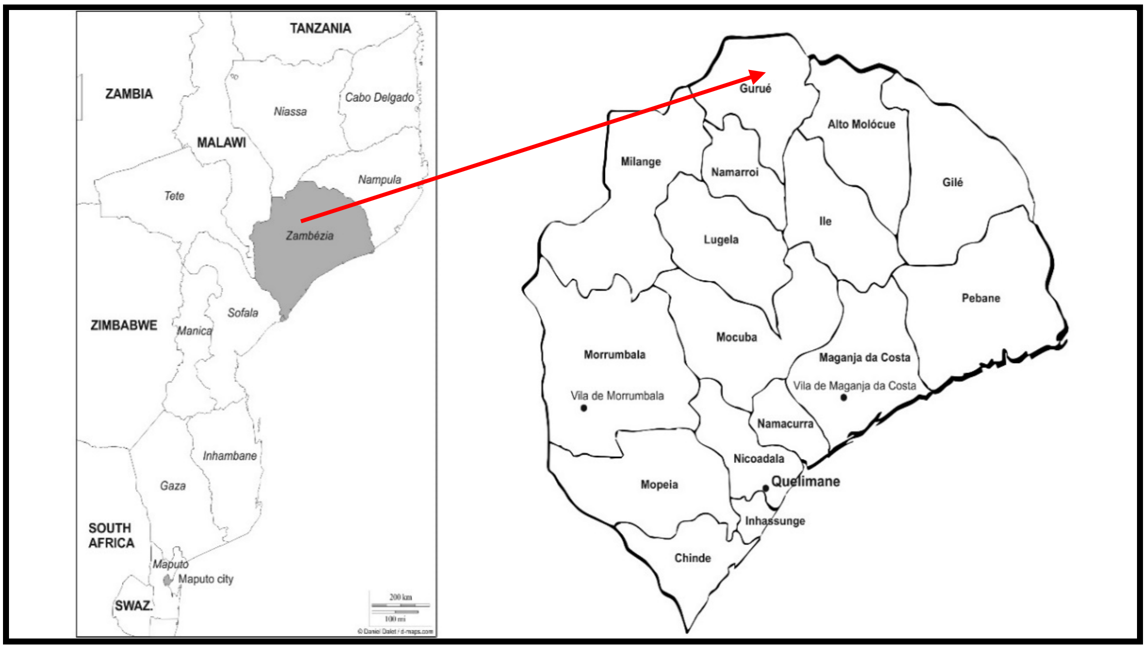


Figure 1. Location of the Gùrué District, Zambézia Province, Mozambique.

The experiment was carried out in Gùrué district, with an area of 5,606 km² and a population of 302,948. Gùrué district is located at an elevation of 734 meters and -15.4635800 (south latitude), 36.9816700 (east longitude). It has a wet-dry climate. Summer daily maximum temperatures range from 30 °C to 34 °C. Winters have temperatures in the range of 17 °C to 20 °C. Typical of tropical climates, winter is usually referred to as the dry season, while summer is called the rainy season. Gùrué's climate has much more rainfall than most of the rest of the province due to the orographic effect of the mountains that surround the town. The average high temperature is 24ºC - 25º C and average rainfall per day is 57 mm to 165 mm (https://www.worldweatheronline.com/gurue weatheraverages/zambezia/mz.aspx). To address the production constraints observed by the farmers at Mepuagiua community, we carried out an experiment at Mepuagiua for two cropping season. During the 2015/16 cropping season, we installed a phosphate experiment using two sources of P and pigeon pea (*Cajanus Cajan*s, L.), while during the 2016 / 2017 wet season we, planted common bean (*Phaseolus vulgaris*, L.) after the harvest of the pigeon pea.

3.4.2 Soil characterization

Soil samples were taken from each experimental plot after pigeon pea harvest to assess suspected gradients of soil pH. Samples of each plot were composites of 3 sub-samples taken from the plot harvest area. Soils were analyzed for soil water pH (1:1 ratio), 0.5 M sodium bicarbonate, soil calcium, magnesium and KCl-extractable aluminum determinations were also made. Below, data from the experimental site are listed in Table 2.

Table 2. Selected soil chemical properties of experimental plots, Mepuagiua community, Gùrué district, Mozambique. Depth 0-15cm.

	pH	**P Bicarbonate**	**Ca^{2+}**	**Mg^{2+}**	**K^+**	**KCl-extractable acidity (largely Al^{3+})**
			mg kg^{-1}		- - - $cmol_c$ kg^{-1} - - -	
Median	5.03	15	0.62	0.53	0.40	0.40
Range	4.56 – 5.66	10 - 47	0.35 – 1.93	0.27 – 1.5	0.04 – 0.85	0.04 – 0.85

Table 3. Selected chemical and physical properties of soil of Mepuagiua community, Gùrué district, Mozambique.

Depth	pH	Soil C	Ca^{2+}	Mg^{2+}	K^+	Sand	Silt	Clay	ECEC	ECEC/clay
Cm		g kg^{-1}	- - - $cmol_c$ kg^{-1} - - -			- - - % - - -			$cmol_c$ kg^{-1}	$cmol_c$ kg^{-1} $\%^{-1}$
0-15	4.9-6.5	10.0-37.0	1.8-17.6	0.85-2.6	0.09-0.62	33-63	7.3-30.5	23.4-45.4	3.44-8.57	7.58-35.5
15-30	5.3-6.3	7.5-33.7	3.1-10.3	1.1-2.0	0.11-0.50	37-61	5.3-24.5	34.4-45.4	5.04-12.9	10.1-50.8

Soil pH was obtained from a 1:1 soil: water ratio, Cations Ca, Mg, were measured in a neutral salt extraction (1 *M* KCl). Potassium was measured in a sodium bicarbonate extractant used for phosphorus. Effective cation exchange capacity was calculated by summing the cations Ca^{2+}, Mg^{2+}, K^+ and KCl-extractable Al.

3.4.3 On-farm experiment

An on-farm experiment was conducted to compare the availability of P supplied by rock phosphate with that of the imported triple super phosphate. The experiment was a randomized complete block design (RCBD) with 3 replicates and 8 treatments per replication (Table 4). An experimental plot consisted of 6 rows; 6 m long and 3 m wide. Furrows were opened for each line of 6 m long per plot using a hoe. Seeds were planted 0.5 m between each row and 0.4 m within the row. Seeds were placed on the left side of the furrow and fertilizer on the right side and then covered with soil. The Evate rock phosphate was applied at 20, 40, 80 and 160 kg total P ha^{-1} and the TSP, which served as the reference P fertilizer, was applied at 10, 20, and 40 kg total P ha^{-1}. Twenty kg of N was applied per hectare as urea and 40 kg of K_2O ha^{-1} was applied as potassium chloride as blanket applications of these nutrients for all treatments. Planting took place on 20 January 2016 and the first weeding was done on 5 February 2016. Harvest took place 27 August 2016 after 220 days of growth.

Table 4. Description of treatments

Treatment	Description (ERP, Kg/ha)	Treatment	Description (TSP, Kg/ha)
T_1	20	T_5	0
T_2	40	T_6	10
T_3	80	T_7	20
T_4	160	T_8	40

3.4.4 Crop selection and crop management

3.4.4.1 Crop selection

The pigeon pea variety selected for the first crop in this rotation experiment (ICAEP00020) has a relatively long growth cycle of 190 days. Local farmers in Central Mozambique and Malawi are accustomed to using varieties of even longer growth cycles of 240 to 270 days (Dr. O. Madzonga, ICRISAT/Malawi, personal communication 2016). ICRISAT/Malawi has introduced varieties of medium duration (160 to 190 days) in the Gùrué district, but adoption seems slow. Local practice is to seed at very low plant populations such as 1 meter apart (Malawi recommendations are to space hills at 90 cm x 90 cm). For this experiment we chose a much closer spacing of rows 50 cm apart with hills placed at 40 cm apart in the row. This plant population still seems too low to obtain maximum grain yield.

3.4.4.2 Crop management

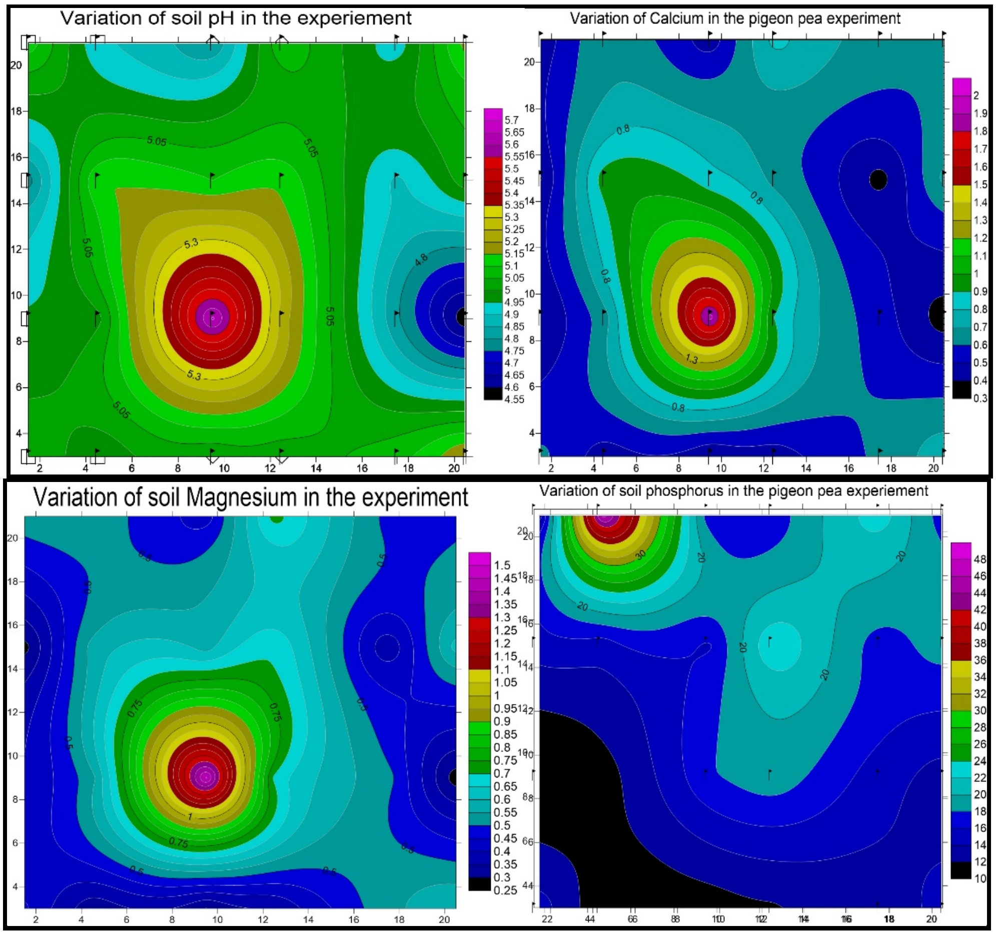
Non-destructive and destructive measurements of six selected plants were taken and recorded at approximately two-week intervals throughout the growth cycle. These measurements included plant height, stem circumference and plant population. At harvest, pigeon pea pods were collected from the four central rows, which comprised a harvest area of 12 m^2. Pods were weighed and air-dried for final weight and yield calculation. Aboveground biomass was also collected, weighted, and sub-samples taken for dry weight calculation.

3.4.4.3 Statistical analysis

A randomized complete block ANOVA was calculated on yields and above ground biomass yields using both Statistix® v. 10 statistical analysis software and JMP (SAS, 2017). The results were plotted using Sigmaplot® v. 12.5 graphics software. Plots of the relationship between grain, biomass, plant height and stem circumference and total amounts of applied P either in soluble TSP form or in the form of rock phosphate were developed. These plots served to quantitatively compare pigeon pea response to the Evate rock phosphate in relation to that of TSP and permitted a comparison of relative solubility and availability of the P in the Evate phosphate. When the ANOVA indicated a significant effect, a linear-response-plateau equation was fitted to the data (Shuai *et al.,* 2003; Nilawonk *et al.,* 2008.) using a Sigmaplot scripting code. This equation permits estimating the amounts of nutrient required to reach maximum yield and the quantitative slope of yield versus applied nutrient (Anderson and Nelson, 1975). Because substantial variation in soil pH was observed among the experimental plots (Table 4), contour plots of soil pH, grain and biomass yields were prepared using the Surfer® version 12.8 software. Individual plot yields and corresponding mean soil measurements for the plot provided the spatial data for the contours. Other plots of yields in relation to soil measurements were developed to explore and quantify the effect of soil acidity on pigeon pea growth and response.

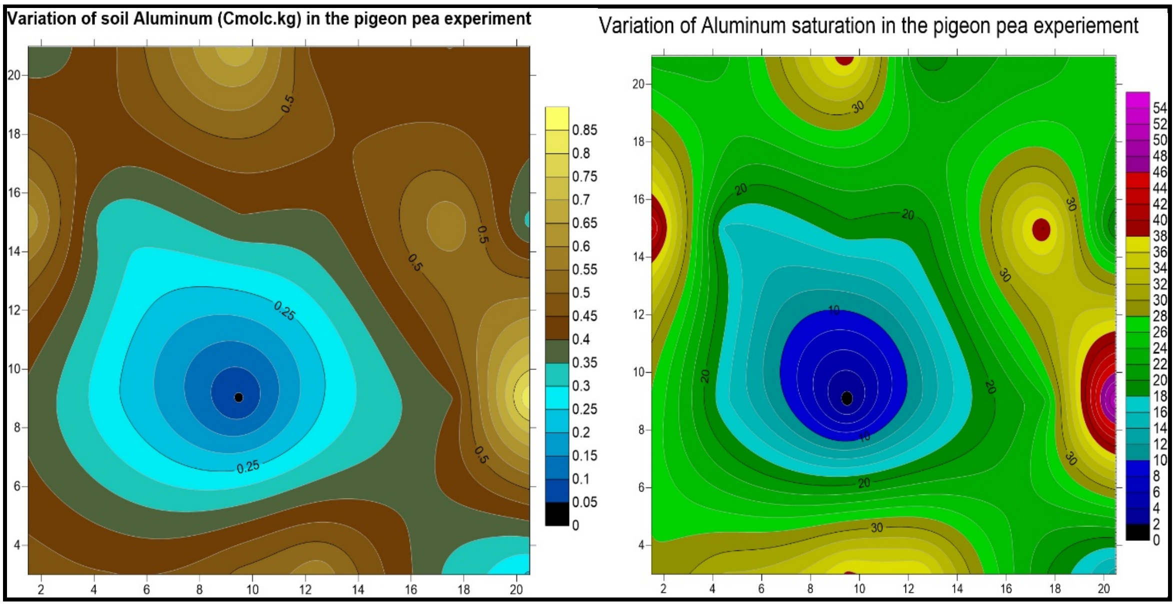
3.5 **Results and discussion**

Before the installation of the experiment, soil samples were collected and analyzed. The purpose of soil sampling was to assess and determine the field uniformity in term of soil plant nutrients to grow pigeon pea and or common bean. Below are presented figures showing the various nutrients variability observed in the experiment.



Contour plots 1 and 4: Variation in soil pH, soil Ca^{2+}, Mg^{2+}, and P in the experiment. The X and Y axes referred to the field plot sizes (centroids, cm). Black color means minimum and the pink color refers to the maximum levels.

Soil measurements per plot basis showed wide range in soil pH, soil Ca^{2+}, soil Mg^{2+} and soil phosphorus. Soil pH ranging from 4.5 to 5.7(acid soil), and low levels of cations Ca^{2+}, Mg^{2+} observed have similar pattern (ranging from 0.3 to 2 cmolc kg^{-1} and 0.25 to 1.5 cmolc kg^{-1}) respectively. As characteristic of an acid soil, soil P varied though indicated low levels (10 to 48 mg/g). These low levels of essential soil nutrients are very low thus it is impossible to grow a leguminous like common bean due to low soil pH, and sensitivity to aluminum. Such field variability might be attributed to burning occurred during field preparation. Farmers gathered grasses, crop residues and burned in the plot center.



Contour plots 3 and 4: Soil $Al^{3+}$and Al^{3+} saturation variation in the Mepuagiua.

The X and Y axes referred to the field plot sizes (centroids, cm). Black color means minimum and pink color maximum levels.

The analysis of soil Al^{3+} and Al^{3+} saturation in the pigeon pea field, varied throughout the field. Although the levels of soil $Al^{3+}$and Al^{3+} saturation were relatively high, pigeon pea was able to grow due to its adaptation to such soils and low soil nutrients. Soil Al^{3+} reached a maximum of 0.85 cmolc kg^{-1}, while Al^{3+} saturation was 54%. It seems that pigeon pea adapted very well to such field variability with grain yield of 1200 kg grain ha^{-1} which is higher than the national yield.

After present the preliminary results of soil before planting pigeon pea, below are presented pigeon grain yield, total applied P, biomass yield as influenced by P sources; ERP and TSP.

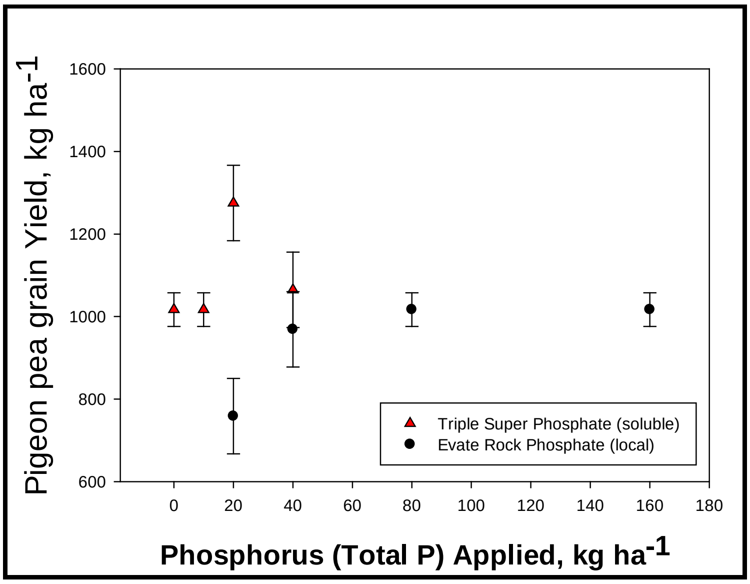


Figure 1. Grain yields of pigeon pea (*Cajanus Cajan*) as influenced by rate and source of phosphate. The bars represent standard errors of treatment means

There was a significant increase in grain yield due to application of ERP ($P<0.045$) and TSP ($P<0.0036$) at different rates after a period of 220 days of pigeon pea growth (Figure 1). A maximum grain yield of 1100 kg ha^{-1} was achieved with application of 20 kg ha^{-1} TSP while grain yields where the Evate rock phosphate was applied at 80 kg ha^{-1} reached around 1000 kg ha^{-1}.

Pigeon pea grain yield at 20 Kgha^{-1} TSP applied was clearly superior than ERP at rate of 80 kg Pha^{-1}, due to several reasons: (1) TSP inorganic fertilizer is highly soluble compared to low solubility ERP (3.5 % citric acid solubility and 0.95 % neutral ammonium acetate solubility). Regardless the lower yield of pigeon pea on ERP, the yields under ERP was higher than the yields obtained at farmer's level in Gùrué district, Mepuagiua community.

An experiment carried out by Magiroi *et al.* (2015) under Kenyan, acid (pH 5.04) Ferralsols consisted of two P sources: TSP and Minjingu PR applied at different levels (TSP—0, 12.5, 25 and 50 kg P ha^{-1}; Minjingu PR—0, 25 and 50 kg P ha^{-1}) and three crops: maize-Mz (*Zea mays)*, common bean-CB (*Phaseolus vulgaris*) and soybean-SB (*Glycine max*). The application of 50 kg ha-^{1} of Minjingu RP provided similar soybean grain yield as 25 kg P ha^{-1}TSP applied. It was also shown that Minjingu PR has a longer residual effect in soils (Kalala and Semoka 2010) and that it was suitable for direct application in the P deficient acidic soil of Western Kenya (Jama and van Straaten, 2006).

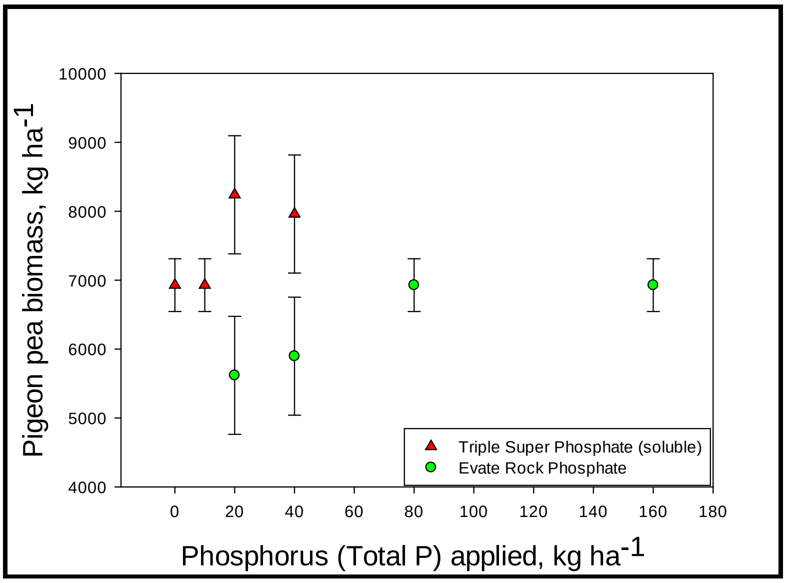


Figure 2. Pigeon pea above ground biomass in relation to source and amount of applied P.

For an application of 80 kg P ha^{-1} as ERP yielded a biomass of approximately 5500 kg ha^{-1} (Figure 2). The application of 20 kg P ha^{-1} of total P applied as TSP, provided maximum pigeon pea biomass yield of 8100 Kg ha^{-1}. An analysis of pigeon pea aboveground biomass in relation to source and rate of applied phosphate revealed essentially the same pattern of response as did grain yield results (Figure 1). The biomass result also indicates that the Evate rock phosphate effectively supplied nutrients to this pigeon pea crop and in this acid, infertile soil.

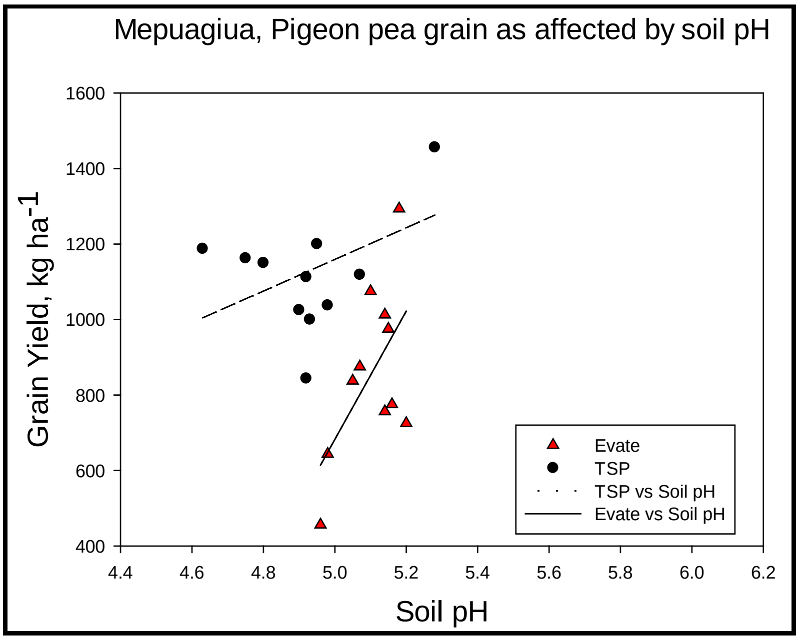


Figure 3. Relationship between grain yield and soil pH of all treatments.

Soil pH varied throughout the field. Pigeon pea yields increased with increase of soil pH. A yield of approximately 1500 Kg ha^{-1} pigeon pea was observed at soil pH 5.2. It seems that the soil condition (low soil pH ranging 4.5 – 5.7) has contributed to dissolution and plant availability, which in turn resulted in higher yields compared to ERP. This variation appears to have resulted from the preparation of the experiment whereby all plant residue from the experimental area was gathered and burned in the plot center, clearly a time efficient alternative, but not optimal for the experimental objectives. A further analysis suggests that, in fact, the pigeon pea did respond to the gradient on soil pH induced by burning of plant residue from clearing (Figure 3).

3. 6 Conclusion

A pigeon pea grain yield of 1000 kg grain ha^{-1} was obtained with an application of 80 kg ha^{-1} of total P added as ERP. By comparison 20 kg P ha^{-1} as TSP was needed to reach a maximum yield of pigeon pea grain. If this relationship was used to estimate relative effectiveness, it is 20/80 or 25%. This research suggests that the ERP can be an effective amendment that can enable food grain production on the acid, infertile upland soils of Central Mozambique. Evate rock phosphate, in this combination of soils and crops, was an effective source of the often limiting nutrient P for food grain production in Mozambique. This rock phosphate has an unusually high level of P

(40.7% P_2O_5), however solubility is low (3.5 citric acid solubility and 0.95 neutral ammonium acetate solubility). These values are high in total P and low in solubility compared with data from Smallberger *et al.* (2010). The solubility of this rock phosphate can be improved by increased surface area with fine grinding, use on acid soils, and with crops of either long duration and / or that acidify their rhizosphere. Use of this potentially very important local fertilizer resource needs to be tested in other conditions and cropping systems whereby the dissolution might be initiated and largely carried out during the pigeon pea cropping period. Other research shows that subsequent crops also benefit from the P released during the pigeon pea phase of the rotation. Additional field experimentation using this rock phosphate are needed to quantify and assess its potential role in increased food crop productivity in Central Mozambique.

Chapter 4: Common bean yield response on different lime rates application in Mepuagiua Community

4.1 Abstract

Rural food insecurity occurs throughout Africa, and Mozambique is no exception. Low soil fertility and high soil acidity limit crop productivity and the mitigation of food insecurity. Common bean (*Phaseolus vulgaris L.,)*, a staple food crop (14% total area of the main legume) and pigeon pea *(Cajanus Cajan L.)* have traditionally been grown throughout the country as subsistence crops. Field experiments were conducted in an attempt to improve food security by increasing yields of pigeon pea and common bean. Factorial amounts of triple super phosphate (TSP) and Evate rock phosphate (ERP) were compared in terms of pigeon pea growth and grain yield. Pigeon pea grain yields of 1 Mg grain ha^{-1} was possible with an application of 80 kg ha^{-1} of total P added as ERP. By comparison 20 kg P ha^{-1} as TSP was needed to reach a maximum yield of pigeon pea grain. This research suggests that the ERP can be an effective amendment for food grain production on the acid, infertile upland soils of Mozambique. For common bean, soil pH was adjusted upward using lime from nearby Nampula Province. Germination and early growth were extremely limited with no lime application, however maximum growth occurred with the modest application of 1 Mg ha^{-1} of lime. Further studies are needed to determine how long the 1 Mg ha^{-1} of lime will continue to support improved common bean growth.

4.2 Introduction

Central Mozambique is sparsely populated (Folmer *et al.,* 1998) and characterized by extensive farming systems in which slash and burn, limited fertilizer use and continuous mono cropping are common, and there is little to no crop-livestock integration. Soils are infertile (Maria and Yost, 2006) and the poor soil productivity is compounded by limited capital resource availability, poverty and limited market participation. A major challenge in central Mozambique is to improve soil and crop productivity to meet the food security and cash needs of smallholder farmers without creating new constraints (Mafongoya *et al.,* 2006).

Grain legume crops provide a good starting point as intensification and diversification options due to their multi-purpose nature (food, fodder and soil fertility) and the small initial capital investment required. Yields of common bean are quite low in most of the regions where this crop is grown. Both biotic and abiotic constraints are responsible for reduced yields. Low soil fertility is the major yield-limiting factor in most of the bean-producing regions (Fageria, 2002; Fageria and Baligar, 2003). Soil acidity also limits crop yield in extensive areas in the world. Calcium deficiency and aluminum toxicity are considered a major yield-limiting factors of tropical and subtropical acid soils (Coleman and Thomas, 1967). By applying lime, Fageria (2001a, 2001b) observed significantly increased grain yields of annual crops such as common bean, corn, soybean, and upland rice grown on Brazilian Oxisols.

Beans are considered the most important grain legume for direct human consumption worldwide, with a global production of ca. 23000t (FAOSTAT, 2015). Among bean species, those of the genus *Phaseolus* are the most widely grown, occupying more than 85% of bean production area globally (Singh, 2001). *Phaseolus vulgaris* L., hereafter referred to as common bean, accounts for 80% of the bean species consumed (Wander, 2007). Common bean is cultivated in a wide range of production systems, representing different climates, soils, cultivars and levels of technology. This research is an attempt to improve food security by enabling an increase in common bean productivity in the Mepuagiua community.

4.3 Goals and objectives

4.3.1 Goal

To improve food security at local and national levels in Mozambique.

4.3.2 Objective

To determine the liming needs or requirement to grow beans on the reddish-brown soils in summit or back slope topographic positions.

4.4 Materials and Methods

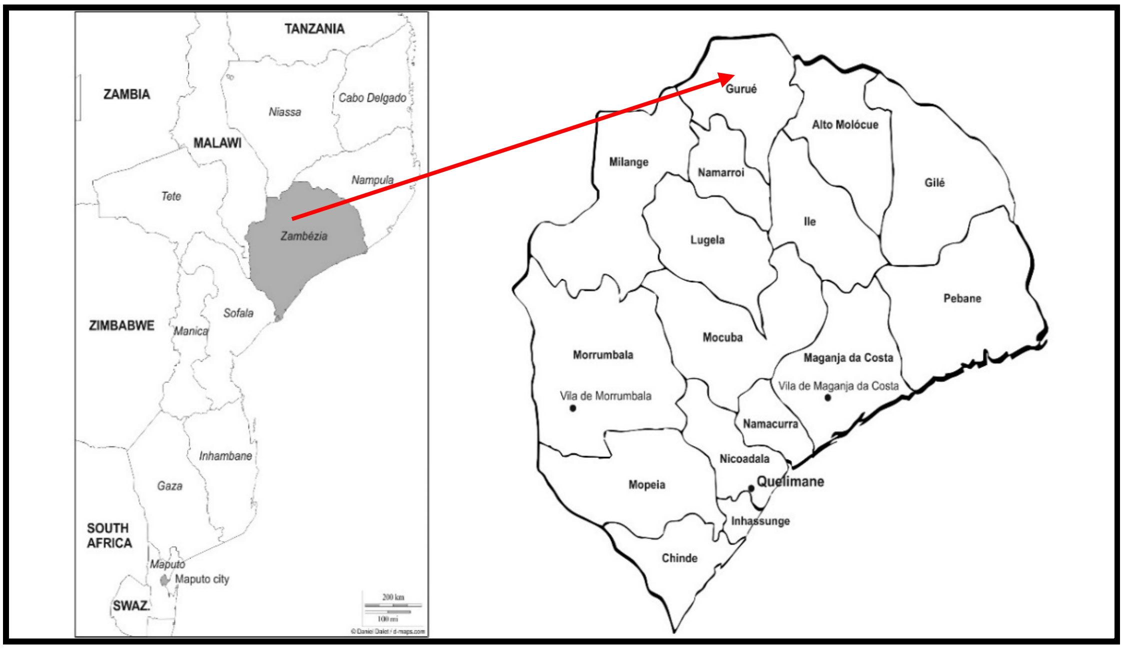


Figure 2. Location of the Gùrué District, Zambézia Province, Mozambique

4.4.1 Site and crop management

4.4.2 Site

Two lime experiments were installed in 2016/2017 cropping season in the Mepuagiua community. The first was located at a summit position (Farmer Noémia) and the second one was located on a backslope position (Farmer Palame) of the catena. Similar experimental design, crop (*Phaseolus vulgaris* L.,) lime rates, planting space and management were used for these two field experiments (Table 2.3). The experiments were carried out in Gùrué district, with an area of 5,606 km^2 and a population of 302,948. Gùrué district is located at an elevation of 734 meters and -15.4635800 (south latitude), 36.9816700 (east longitude). Summer daily maxima temperatures range from 30 °C to 34 °C. Winters have temperatures in the range of 17 °C to 20 °C. Typical of tropical climates, winter is usually referred to as the dry season, while summer is called the rainy season. Gùrué's climate has much more rainfall than most of the rest of the province due to the orographic effect of the mountains that surround the town. The average high temperature is 24 ^oC- 25 ^oC and average rainfall per day is 57 mm to 165 mm. (https://www.worldweatheronline.com/gurue-weather-averages/zambezia/mz.aspx).

4.4.2.1 Crop management

Four rates of lime were applied and incorporated: 0, 1, 3, and 6 Mg ha^{-1}. Fertilization consisted of urea (46% N) as source of nitrogen and TSP (45% P_2O_5) as source of phosphorus. These fertilizers were applied 5 cm apart by hand at 20 kg ha^{-1}. The land was subsequently prepared for seeding by drawing furrows 15 cm deep using hand hoes. At seeding V0, common bean (*Phaseolus vulgaris*, L.) of NUA45 variety, was spaced at 45 cm by 10 cm with 1 plants per station, after thinning one (222222 plants ha^{-1}).

4.4.3 Selection of experimental site and preparation

To address the production constraints observed by the farmers at Mepuagiua community, we carried out two lime experiments at Mepuagiua – Central area. Soil samples were collected before carrying out the experiments at 0 – 20 cm and 20- 40 cm deep using a soil auger. Two composite samples per plot were prepared. Soil pH was obtained from a 1:1 soil: water ratio at Sherman Lab, University of Hawaii at Manoa.

Table 2. 1. Description of the treatment structure

Treatments	Description (lime_ tones ha^{-1})
T1	No, N, P, or lime
T2	20N, 20P, 0 lime
T3	20N, 20P, 1 ton lime
T4	20N, 20P, 3 tons lime
T5	20N, 20P, 6 tons lime
T6	20N, 0P, 3 tons lime
T7	0N, 20P, 3 tons lime

N- Nitrogen, P- Phosphorus

4.4.4 Experimental design

A randomized complete block design (RCBD) was used, with three replications and seven treatments (Table 1) at both farmers' fields. Plot sizes were 3.0 m by 6.0 m. The total area was 0.1 ha (1,152 m^2) without borders. Nampula province lime was applied and subsequently bean was planted. Common bean (*Phaseolus vulgaris*, L.) of NUA45 variety was used without considering farmers common bean preferences.

4.5 Statistical analysis

A randomized complete block ANOVA was calculated on number of plants, plant height, fresh pod weight, plant biomass without pods and dry grain weight using the Statistix® v. 10 statistical analysis software. When experimental effects were significant plots a linear-response-plateau equation was fitted to the data using a script developed using Sigmaplot® v. 12.5 graphics software. Response plots between number of plants, plant height, fresh pod weight, plant biomass without pods and dry grain weight and different lime rates applied, N, P were developed. These linear-response-plateau plots served to quantitatively compare common bean response to the different lime rates applied, and nitrogen and phosphorus. It also permitted to observe if the yields were due to nitrogen or phosphorus addition or lack of soil calcium or soil phosphorus.

4.6 Results

4.6.1 Results from Noémia's experiment

4.6.1.1 Plant growth as measured by plant population

In this section, results of farmer Noémia's experiment are first presented followed by those of farmer Palame. The responses to rates of lime application and incorporation and nitrogen and phosphorus application are organized and interpreted in separate sections of this chapter. The presentation begins with the analysis of data from the response to lime application then responses to nitrogen and then phosphorus.

4.6.1.2 Plant growth as measured by plant population

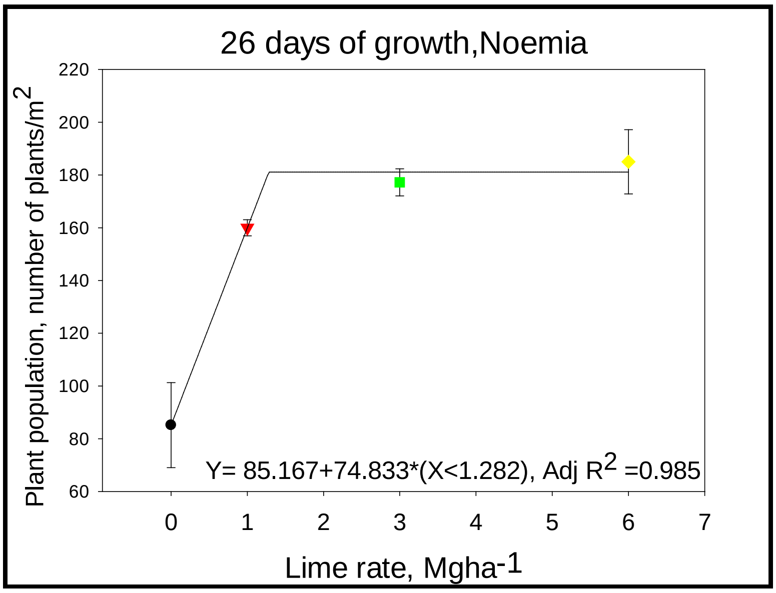


Figure 1. Plant population of common bean (Phaseolus vulgaris, L.) as influenced by lime rate. The bars represent standard errors of treatment means.

A significant increase in the bean plant population ($P<0.0003$) was observed after 26 days of plant growth as influence by lime rate. The bean plant population was approximately 85 plants / m^2 without lime application and incorporation. When 1.28 Mg ha^{-1} of lime was applied and incorporated, approximately 180 plants / m^2 were counted. For each Mg ha^{-1} of lime applied, we observed additional 75 plants per square meter. After 35 - 40 days of plant growth, we observed substantial reduction of rainfall. Consequently, plant water stress and symptoms of pest and diseases occurred severely stunting further growth and development.

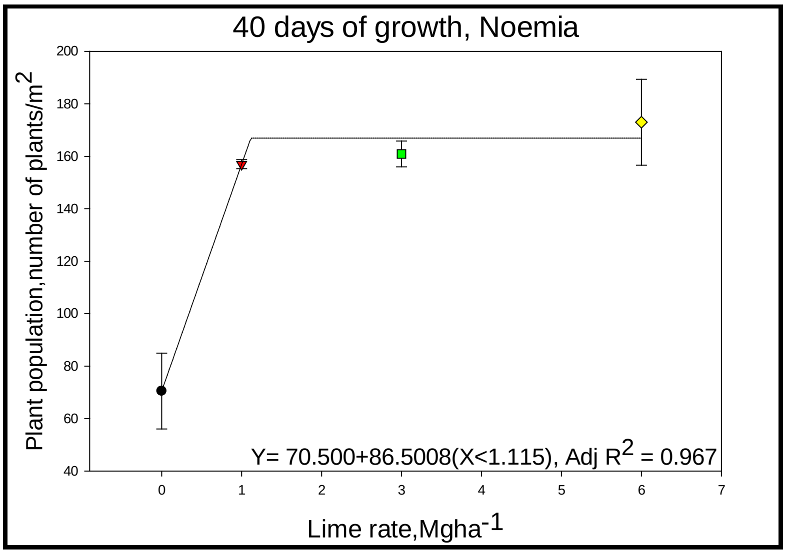


Figure 2. Plant population of common bean (Phaseolus vulgaris, L.) as influenced by lime rate. The bars represent standard errors of treatment means.

Significant increase ($P<0.0003$) was observed in the bean plant population after 40 days of growth. Approximately 71 plants / m^2 were measured and recorded with no application and incorporation of lime, while approximately 165 plants as maximum was counted in the experiment. We also noted an increment of about 87 plants per Mg ha^{-1} lime applied and incorporated. The justification presented for figure 1 above, applies for figure 2 as well.

4.6.1.3 Plant growth as measured by plant height

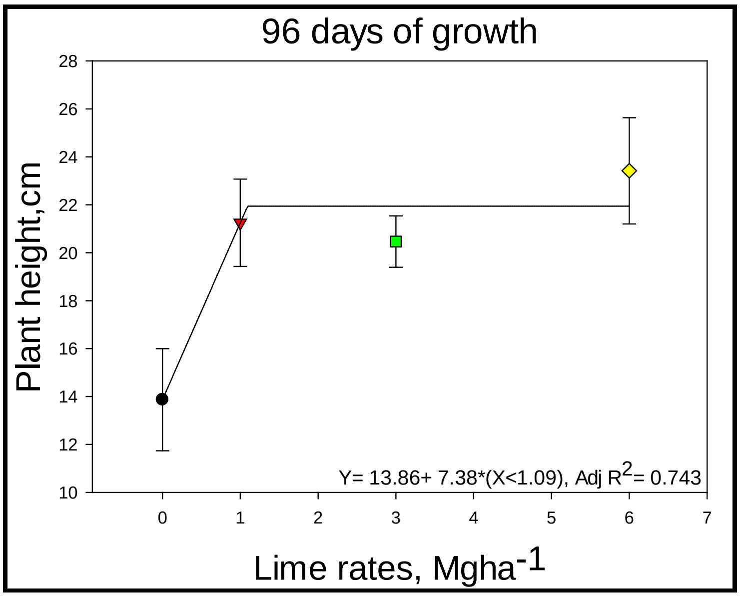


Figure 3. Bean plant height (Phaseolus vulgaris, L.) as influenced by lime rate. The bars represent standard errors of treatment means.

There was a significant increase ($P<0.033$) on bean plant height after 96 days of growth due to lime application and incorporation. Bean plant height was approximately 14 cm in height with no application and incorporation of lime. A maximum bean height was measured after the application and incorporation of 1.09 Mg ha^{-1}. For each Mg ha^{-1} of lime applied and incorporated, we observed an increase in bean plant height of 7.38 cm in height. With the application and incorporation of lime, substantial rainfall in the area at germination stage and good soil moisture for at least two months, tall plants were observed and measured after the application and incorporation of 1.09 Mg ha^{-1}. These factors may have considerably contributed to the bean plant growth.

Souza *et al.* (2008) carried out a liming experiment on a heavy clay soil in Ponta Grossa, Paraná State, Brazil in the 2003/2004 summer rainy growing season with the Iapar 81 cultivar, a type II common bean. The experimental design was a randomized block with four replications, and treatments in a 4 x 4 factorial. Four different plant populations (100.000, 200 000, 300 000, and 400 000 plants ha^{-1}) and four NPK-liming levels (0.0, 0.5, 1.0, and 1.5 t ha^{-1} recommended doses of NPK and lime). A maximum plant height of 56.07 cm was measured with application and incorporation of 1.5 t ha^{-1} lime, meaning 48% linear increment. Similar results were obtained using common bean type III cultivar (Souza *et al.,* 2002) and with Iapar 81, tipo II cultivar used in the previous work (Souza *et al.,* 2004a, Souza *et al.,* 2004b). Moreover, the author attributed such plant height increment to great plant nutrient availability with allowed great absorption and bean plant growth. The results also are in agreement with the findings of Chinanshuk Ghosh *et al.* (2014) that reported plants of French bean grew up to a maximum (25.15 cm) with 100% mustard oil cake ha^{-1}.

4.6.1.4 Effects of Nitrogen and Phosphorus on bean growth

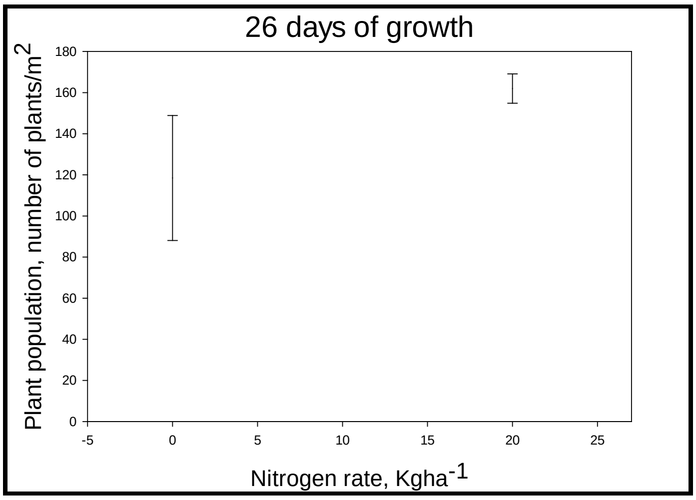


Figure 4. Plant population of common bean (Phaseolus vulgaris, L.) as influenced by nitrogen rate. The bars represent standard errors of treatment means.

There was a significant increase ($P<0.0358$) in the bean plant population after 26 days of growth in height. After the application of 20 Kg ha^{-1} N, a maximum of 161 plants / m^2 were counted. This N response is evidence that the soil N was too low to meet the plant requirement. No pest and diseases attacks were observed at the germination stage and good rainfall distribution might be factors responsible for increment in number of plants. We also assume that the application and incorporation of lime as reduced the soil acidity or increased soil pH as the bean plant roots were enable to explore deeper soil layers and uptake needed nutrients.

Study conducted by Tang *et al.* (2017), on planting density and nitrogen fertilization effect on dual-purpose hemp (Cannabis sativa L.) cultivation, showed that increasing nitrogen fertilization rate from 0 to 120 kg N ha^{-1} resulted in overall increases in plant height and stem diameter by 22% and 20%, respectively. On the other hand, the same author observed that by increasing plant density from 30 plants m^{-2} to 240 plants m^{-2} resulted in overall decreases in plant height and stem diameter by 15% and 37%.

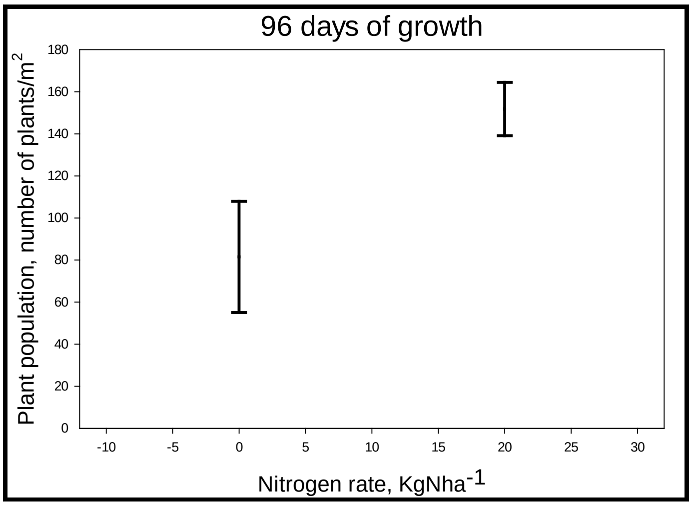


Figure 5. Plant population of common bean (Phaseolus vulgaris, L.) as influenced by nitrogen rate. The bars represent standard errors of treatment means.

There was a significant increase ($P<0.014$) in the bean plant population after 96 days of plant growth. A total of 152 plants / m^2 were counted after the application of 20 kg N ha^{-1} of as urea. Even though lime was well applied and incorporated, a reduction of plant population was recorded. Long period without rain, incidence of termite attacks and water stress may have negatively contributed to such reduction. Additionally, low plant density is another factor that suggest such low bean plant population at 90 days of plant growth.

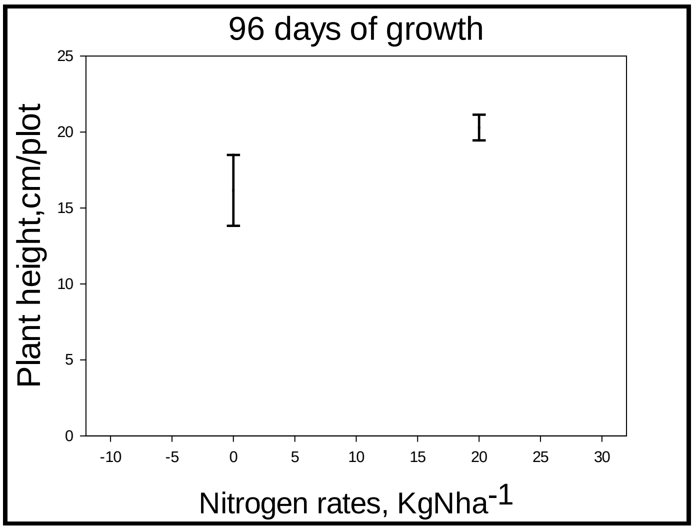


Figure 6. Plant height of common bean (Phaseolus vulgaris, L.) as influenced by nitrogen rate. The bars represent standard errors of treatment means.

We observed a significant increase in the plant height ($P<0.019$) as influenced by N applied as urea. A plant growth in height of about 20 cm height was measured after the application of 20 kg N ha^{-1} as urea. We observed similar pattern in the bean plant height when 1.09 Mg ha^{-1} lime applied and incorporated after 96 days of bean growth. So, lime application and incorporation together with soil moisture might have improved the bean root expansion vertically and horizontally and consequently better nutrients uptake which contributed to tall plants.

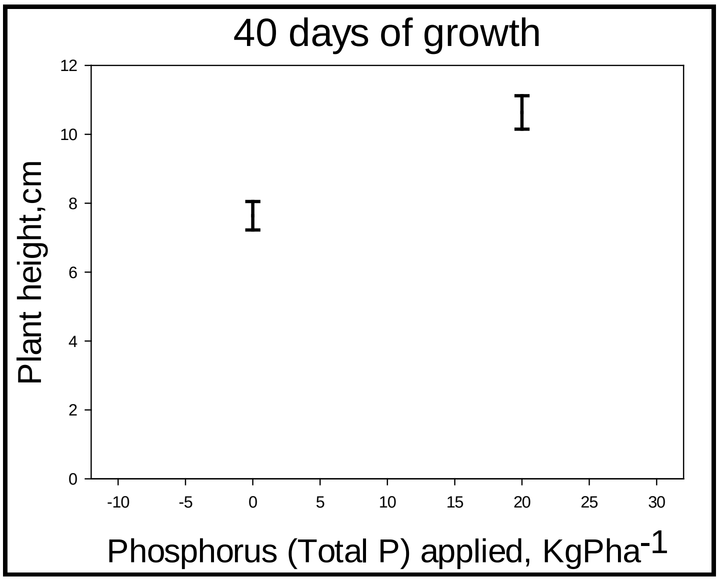


Figure 7. Plant height of common bean (Phaseolus vulgaris, L.) as influenced by phosphorus application. The bars represent standard errors of treatment means.

There was a significant increase on the bean plant height ($P<0.0445$) after 40 days of bean growth as influenced by the phosphorus application. With no application of P, bean plant height measured 8 cm height. Approximately 11 cm height, bean plant growth responded after the application of triple super phosphate as source of phosphorus at rate of 20 kg P ha^{-1}. Phosphorus response in this treatment is an evidence of phosphorus was lacking and should be added to the soils. The reduction of soil acidity at summit position due to lime application and incorporation, substantial soil moisture and no records of pest and diseases in the field, might be the reasons of good response in bean plant height as TSP as source of phosphorus at rate of 20 kg P ha^{-1} was applied.

Similar response on plant height was observed by Modupeola *et al.* (2013) in the Guinea Savannah zone of South Western Nigeria when investigated phosphorus fertilizer and plant density required for the optimum growth and yield of ginger. The results of the investigation showed that the plant height of ginger increased significantly with the increase of phosphorus. The tallest plant (65.1 cm) was obtained from the dose of 60 kg ha^{-1} P at 45 X 50 cm. The shorter plant height was found from the dose of 0 and 15 Kg ha^{-1} P. In the same work, the authors found that the combine of spacing and phosphorus rate influenced all ginger characters. However, increasing trend of plant height with increasing rate of P was also reported by Kumar *et al.* (2002) in trilobus and on mustard plant height (Anikumar *et al.,* 2001).

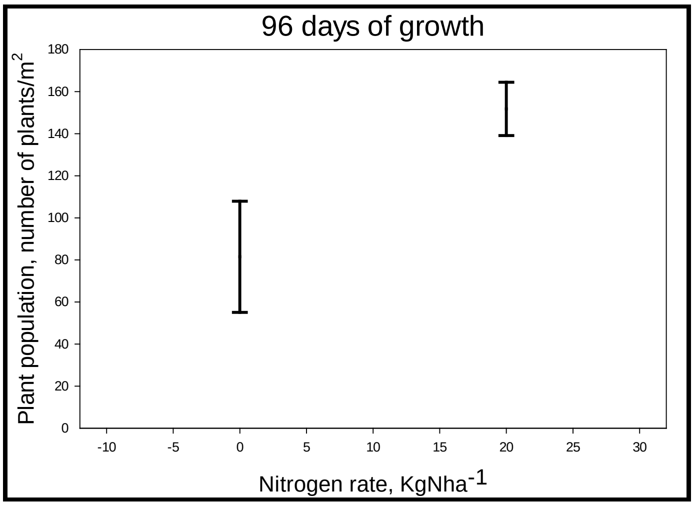


Figure 8. Plant population of common bean (*Phaseolus vulgaris*, L.) as influenced by phosphorus rate. The error bars represent standard errors of treatment means.

Significant increase in bean plant population was observed ($P<0.0114$) as influenced by the rate of total phosphorus applied in the hectare basis. After the application of 20 kg P ha^{-1}, we counted a total of 150 plants / m^2 after 96 days of growth. Phosphorus response was observed after the application of 20 kg P ha^{-1} as TSP.

4.7 Conclusion and recommendation

In the Mepuagiua community, farmer Noémia's field was located at summit position and from 26 to 96 days of bean plant growth observed significant increase in two main dependent variables; plant population and plant height as influenced by the rate of lime. When lime applied and incorporated, 1.28 Mg ha^{-1} provided a maximum plant population of 180 plants / m^2 was and 165 plants / m^2, when 1.11 Mg ha^{-1} applied and incorporated. Tallest plants (22 cm) were observed and measured when 1.09 Mg ha^{-1} lime applied and incorporated after 96 days of bean growth compared to 20 Kg ha^{-1} P and N in a period of 40 – 96 days of bean plant growth, 11- 20 cm of height, respectively. Measurements done in the 96^{th} day of bean plant growth in plant population as influenced by N and P, counted and registered 152 plants / m^2 when 20 Kg N ha^{-1} applied. Less plants (150 plants / m^2) were counted at referred period when 20 Kg ha^{-1}TSP applied as source of P. Looking at Mozambican farm perspective, 1.11 Mg ha^{-1} lime and 20 Kg ha^{-1} TSP would be the most recommended to produce bean at summit position at Mepuagiua community.

4.6.2 Results from Palame's experiment

4.6.2.1 Bean plant growth as measured by plant height

The experiment was carried out at the beginning of 2016 / 2017 cropping season involving common bean (*Phaseolus vulgaris*, L.) crop, application and incorporation lime rate, nitrogen and phosphorus. Rate of lime application and incorporation responses, nitrogen and phosphorus application results are organized and interpreted at below of this section chapter. The results presentation starts with response to lime application and incorporation and then phosphorus responses. No results on nitrogen application is presented because there was no significant increase on the dependent variables.

4.6.2.1 Plant growth as measured by plant population

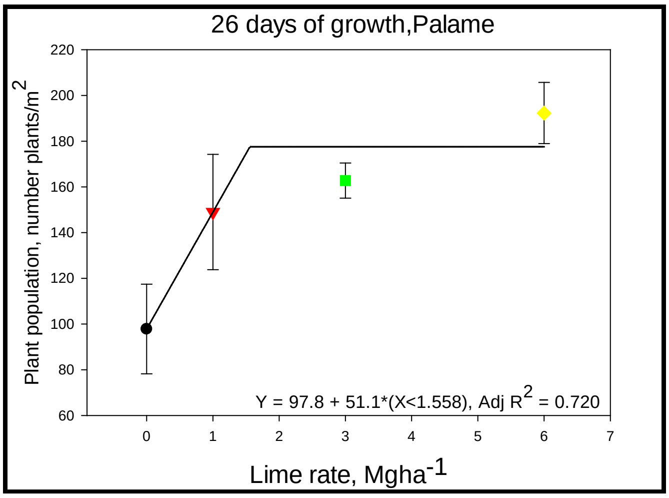


Figure 9. Plant population of common bean (Phaseolus vulgaris, L.) as influenced by lime rate. The bars represent standard errors of treatment means.

After 26 days of bean growth, significant increase (P< 0.04) was observed in the bean plant population. When lime was not applied, a minimum of 98 plants / m^2 was registered, while a maximum of 176 plants / m^2 was achieved with an application of 1.558 Mg ha^{-1} of lime at the same period of time. Bean plant population increased 51 plants / m^2 per $Mgha^{-1}$ lime applied. Lime application and incorporation, good soil moisture and no pest and diseases incidence, lime might have reacted very well with the soil and achieved a maximum plant density with application and incorporation of 1.5 Mg ha^{-1}. The bean plant might also be capable to develop deeper and wider root structure compared to no lime application treatment, since bean is sensitive to soil acidity.

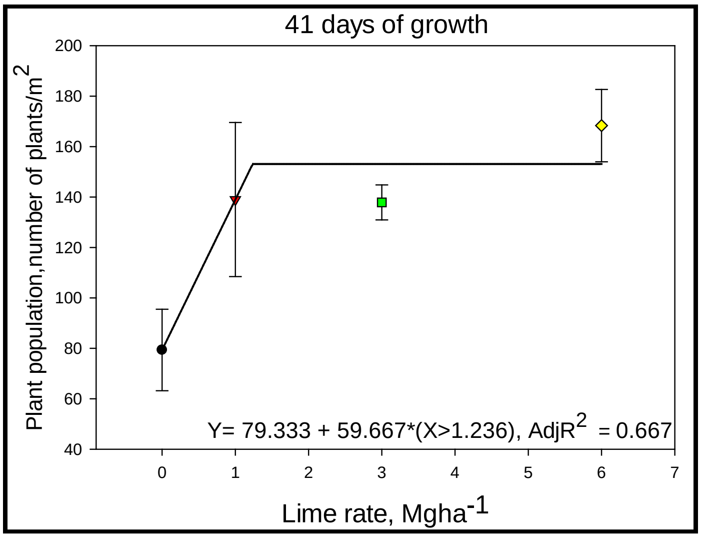


Figure 10. Plant population of common bean (Phaseolus vulgaris, L.) as influenced by lime rate. The bars represent standard errors of treatment means.

After 41 days of bean growth, a significant increase (P<0.0654) was observed on the bean plant population. When lime was not applied, a minimum of 79 plant / m^2 was measured, while a maximum of approximately 153 plants / m^2 was achieved with an application of 1.2 Mg ha^{-1} of lime. There was an increase of 60 plants / m^2 as Mg ha^{-1} lime applied. At the backslope position, factors such as high amount of rain in short period of time followed by long periods of no rain and termites and pest attacks might have contributed to low plant density (plant death and or reduced germination). In contrast, significant increment on plant density was observed due to lime application and incorporation. These results might be attributed the fact that lime has reduced soil acidity considerably at the backslope position.

4.6.2.2 Effect of phosphorus on bean plant population

After present figures of responses in bean plant population as per lime rates applied and incorporated, below are presented figures related to bean plant height and bean plant population as influenced by the phosphorus application at 20 kg P ha^{-1} at farmer Palame's field (backslope position).

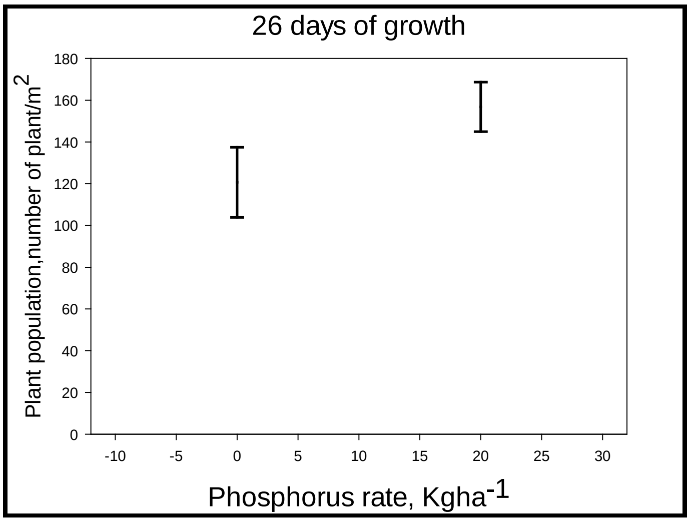


Figure 11. Plant population of common bean (Phaseolus vulgaris, L.) as influenced by phosphorus rate. The bars represent standard errors of treatment means.

On 26th day of bean plant growth, a significant increase (P<0.0072) was observed in the bean plant population as influenced by phosphorus application. With no application of phosphorus, there was a recorded 138 plants / m^2, while 169 plants / m^2 were counted where phosphorus was applied at rate of 20 kg P ha^{-1}. With application of 20 kg P ha^{-1}, responses on plant were observed in the experiment.

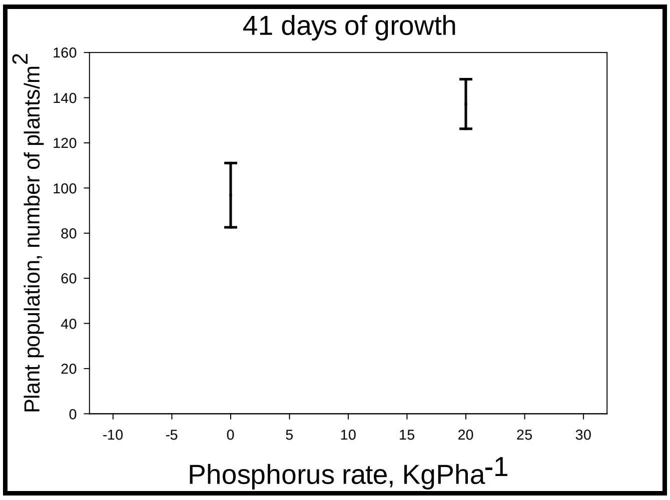


Figure 12. Plant population of common bean (Phaseolus vulgaris, L.) as influenced by phosphorus application. The bars represent standard errors of treatment means.

A significant increase (P<0.0016) was observed in bean plant population after 41 days of bean growth in the Mepuagiua district at backslope position of the catena. Approximately, 111 plants / m^2 were counted where phosphorus was not applied. In contrast, a total of 147 plants / m^2 were counted as a result of 20 Kg ha^{-1}phosphorus applied. After 41 days of plant growth, plant population / m^2 dropped from a total of 169 plant /m^2 to 147 plants / m^2. This reduction in plant population occurred due to devastated termite and ant attacks, low soil moisture, low plant density and even improper choice of the bean plant variety by the researchers that is locally adapted. We also think that, the soil amendment was not well applied and incorporated due to use of rudimentary instruments. Moreover, the lime reaction time might be shorter than the recommended to reduce soil acidity (at least a month before planting). Farmers did not know the use and the benefit of a soil amendment. The second important aspect was that farmers did not report to the field technicians when they observed the termites and diseases attacks in the bean crop in order to prevent severe damage and plant death. A good field scout would be useful to prevent such losses by ensuring high plant density, correct soil amendment application and incorporation in the Mepuagiua soils. In general, at Palame's field, there was no significant response in the dependent parameters after 40 days of plant growth. Evidences by field visits proved that the rains stopped after 40 days of plant growth (Biomass production - Flowering stage) and contributed to plant death, outbreak of pest and diseases lead to no pods formation. There was clear evidence that roots could not uptake nutrients because of lack of soil moisture to occur or perform and biological activity.

Farmer Palame's experiment was located at the backslope position and only significant increase in plant population was counted as per application and incorporation of lime and application of TSP. A total of 176 plants / m^2 was counted after the application and incorporation of lime at 1.55 Mg ha^{-1} after 26 days. After 41 days of bean growth at backslope position, 147 plants / m^2 were counted and registered after 20 Kg ha^{-1} TSP applied. From a Mozambican farmer point of view, farmers may apply and incorporate lime at 1.23 $Mgha^{-1}$ and 20 $Kgha^{-1}$ TSP for best results particularly in plant population per m^2.

4. 8 Conclusion

Farmer Noémia had significant response in plant population and plant height as incorporation and application of lime and application of urea and TSP at 20 Kg ha^{-1}.

For better results, we recommend to plant local common bean variety at the summit and backslope positions using farmer's local adapted common bean variety, irrigation, increase plant population per hectare (300.000 plants per ha) in combination with locally available limestone at 1.11 Mg ha^{-1} and 20 kg ha^{-1} TSP to achieve bean potential yield.

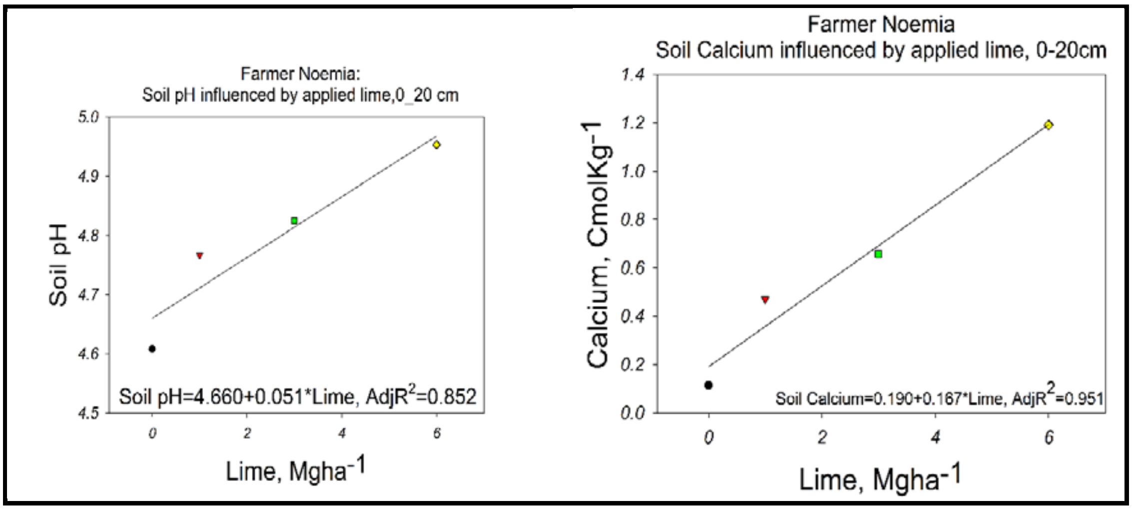
4.9 Conclusion and recommendation for Noemia and Palame's experiments

Plant population and plant height at both locations as influenced by lime rates and urea and TSP application provided similar plant growth patterns at intervals ranging from 26^{th} to the 96^{th} days of bean growth. These and other dependent variables have potential to be improved if taken into consideration, particularly the choice of seeds (common used by local farmers and adapted to local environment), soil management, irrigation, identification of pest and diseases outbreak as well as its control. We also recommend that similar experiment must be installed in different areas and part of the catena in order to identify the right amount, plant spacing that fits the best local condition to improve the crops yield and reduce food insecurity at targeted areas of the country.

4.9.1 Post-harvest soil data

After 98 days of bean growth in the Mepuagiua community, soil data of two farmers' field (Summit and backslope position) were collected and analyzed in Hawaii at Agricultural Diagnostic Services Center (ADSC) laboratory. The purpose of the soil data collection after harvest, was to understand and to assess the agronomic effectiveness of the material applied and incorporated in the farmers' field (Nampula limestone) to produce common bean in those acid reddish- brown soils of Mepuagiua community.

Below, farmer Noémia and farmer Palame's field results are interpreted and summarized.



Figures 1 and 2: Soil pH and soil calcium as influenced by applied lime, 0-20cm.

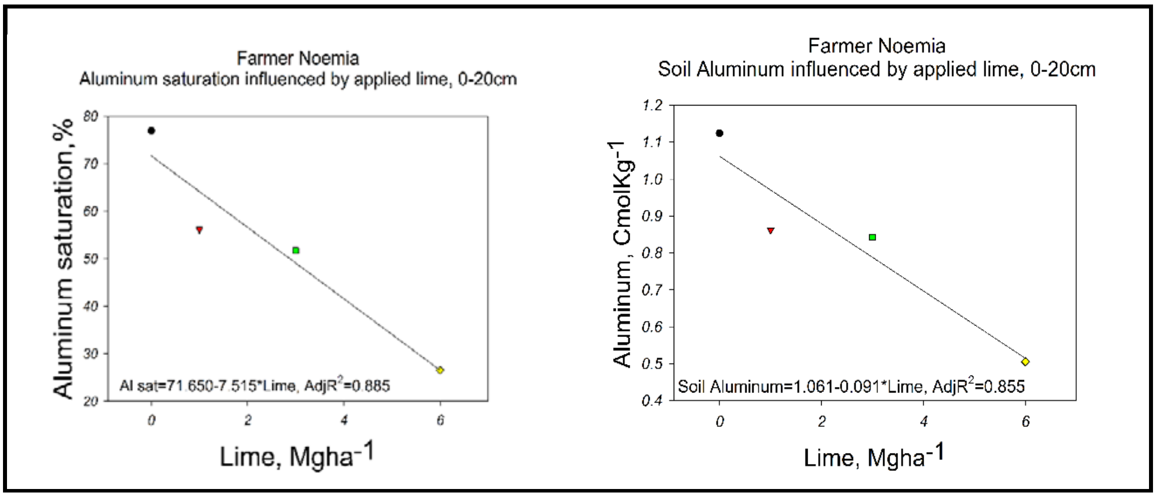
There is relationship between soil pH and soil calcium as lime rate increases. Soil became less acid or soil pH and soil calcium level increased with increment of applied lime per hectare basis (Figure1 and 2).

At farmer Noémia's' field, initial soil pH was 4.66 and soil calcium was 0.190 cmol kg^{-1}, before the application and incorporation of lime at summit position. These observed soil condition were not ideal to grow common bean in the area, therefore lime was applied and incorporate before the crop planting.

A significant increase in soil pH units of 0.051 and of 0.190 cmol kg^{-1} of soil Ca per Mg lime ha^{-1} was observed and registered at summit position. Moreover, both soil pH (6) and soil Ca (1.2 CmolKg^{-1}) registered a maximum level after the application and incorporation of 6 Mg of lime ha^{-1}.

Despite the fact that soil pH and soil Ca level increased at summit position after the application and incorporation of lime, soil condition did not reach the optimum status or and level to bean to grow.

Irregular rain fall distribution in the area, inappropriate farmer seed selection, pest and diseases attacks appeared to be the main factors that negatively affected bean growth, causing bean to fail in the Mepuagiua community.

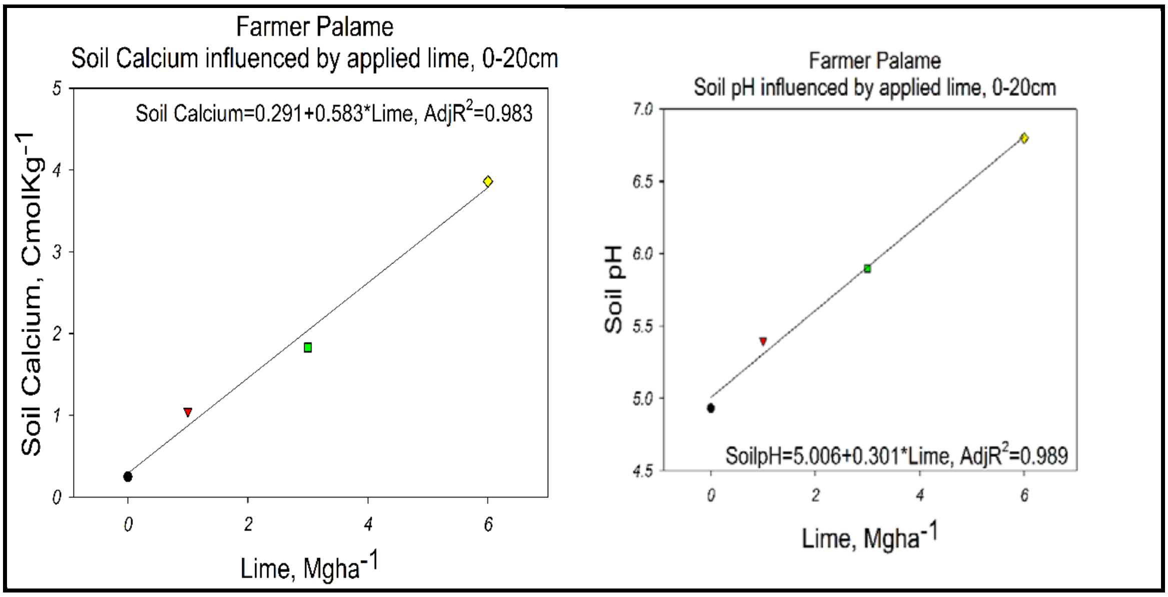


Figures 3 and 4: Soil aluminum and aluminum saturation decreased as influenced by applied lime, 0 – 20 cm

A significant reduction of both soil aluminum and aluminum saturation was observed after the applied lime (Figures 3 and 4). Soil aluminum reduced from a maximum of 1.12 to a minimum of 0.5 after the application and incorporation of 6Mgha^{-1}lime. A reduction of 0.091 cmol kg^{-1} Al^{3+} per ton lime was registered.

A significant reduction of Al^{3+} saturation and of soil toxicity was observed after application and incorporation of 6 Mg ha^{-1} lime, from a maximum of 71.6 % to a minimum of 26 %. Despite this significant reduction of soil toxicity (7.5 % Mgha^{-1} lime), common bean did not grow well and complete the growth cycle.

Apart from rainfall, pest and disease attacks mentioned, another factor associated is that common bean is very sensitive to soil aluminum. A second aspect must be the linked with soil nutrient requirements such as phosphorus, calcium and magnesium were not available at such low soil pH.



Figures 5 and 6. Soil Calcium as influenced by applied lime, 0 – 20cm.

A positive relationship between soil pH and soil calcium was observed as per lime applied and incorporated at backslope position in the farmer Palame's field. Initial soil pH of 5.0 and soil Ca, 0.291 cmol kg^{-1} was measured before the application and incorporation of lime at farmer Palame's' field.

Even though soil pH reached a maximum of 6.8 and 3.8 cmol kg^{-1} of Ca after the application and incorporation of lime, common bean at backslope position did not grow.

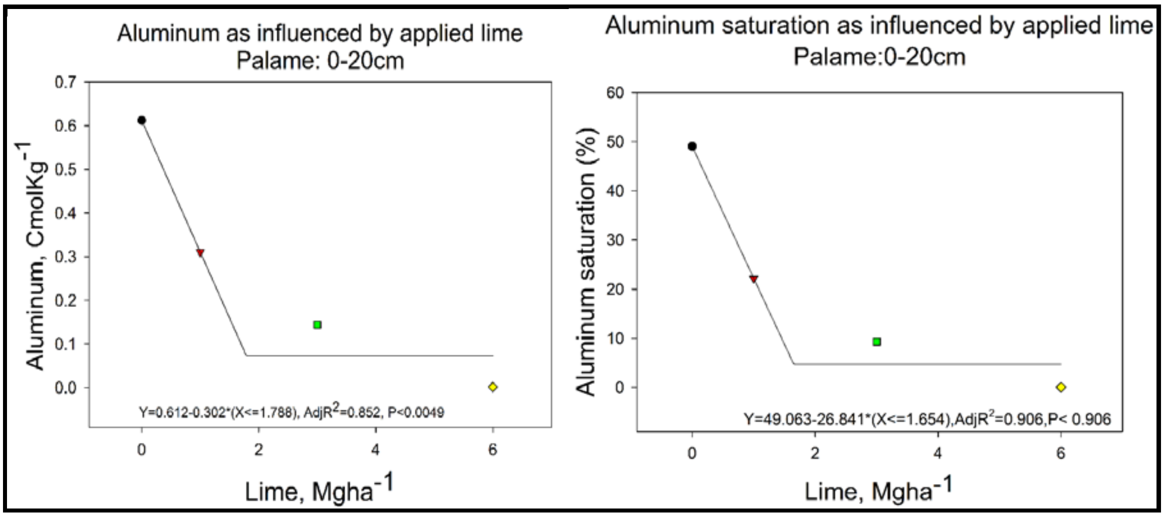


Figure 7 and 8. Al^{3+} and Aluminum saturation (%) as influenced by applied lime, 0 – 20cm.

There is similar trend or pattern on the amount of applied lime to neutralize soil acidity and reduce soil toxicity in the figures above (Figure 7 and 8). Aluminum saturation significantly decreased from 49 % to 4.6% after the application and incorporation of 1.654 $Mgha^{-1}$ and 26.8 % per Mg ha^{-1} lime.

On the soil Al^{3+}, when 1.78 Mg ha^{-1} lime was applied and incorporated, soil aluminum significant reduced from 0.6 to 0.06 cmol kg^{-1}. Bean did not grow and did not complete the growth cycle at Palame's' field, even though similar significant reduction on soil toxicity was observed.

Another similarity was that soil pH compared to soil Al^{3+} and Al^{3+} saturation. Soil pH significantly increase approximately 10 fold as soil Al^{3+} and Al^{3+} saturation seems to be reduced by the same amount.

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Summary

Two experiments were conducted in the Mepuagiua community in 2014/15 and 2016/2017 cropping season involving important leguminous crops, pigeon pea and common bean, in Mozambique. Phosphate and one limestone experiment were located at the summit topographic position, while the second lime experiment was located at the backslope position in the reddish – brown, low soil P level and infertile soils of Mepuagiua community**.** Pigeon pea, in combination with locally available Evate rock phosphate, provided greater yields than the national level of about 1200 kg ha^{-1} with application of 80 kg ha^{-1} of total P.

In contrast, lime experiment at both locations of the soil catena, did not provide improve grain yields. Significant responses were observed on the plant height, plant density / m^2 as per different of lime were applied and incorporated and N and P applied. Biotic and abiotic factors contributed to this failure such as termites and ant attacks, improper selection of local bean variety by the researchers and long periods without rainfall. Another critical factor is that farmers from Mepuagiua do not believe that common bean can be possible be grown at summit and backslope position as their past experience. As recommendation, ERP can potentially be used as soil amendment supplying phosphorus to these infertile, acid soils and increase food production, if it is finely ground and incorporated in the soil. Due to several advantages of pigeon pea compared to common bean, as well as higher pigeon pea yields obtained than the national level, we recommend the use of local pigeon pea variety to be in these reddish-brown acid soils of Mepuagiua community. More limestone and phosphate experiments must be conducted in order to evaluate the agricultural potential of these naturally available resources to increase food production and reduce food insecurity in the country.

The gap between farmers and scientist must be reduced by improving the communication channels, conducting additional field trials and demonstrations, and considering farmers' priorities in their local environment throughout the target communities. Plant responses of plant height, plant density per m^2 were registered and observed as per application of nitrogen and phosphorus at rate of 20 kg ha^{-1} P as TSP and N as source of urea in the lime experiment at both farmers' fields. In order to get better plant common bean growth, these and other soil nutrients essential for bean production must be at plant requirement levels in the soil. However, significant response was observed in the lime treatments and these nutrients should be added either as organic or inorganic fertilizers. On the unexploited resource, limestone, a particle size analysis and calcium carbonate effectiveness evaluation of lime is needed in order to assess and evaluate its agricultural potential for acid soil of Mepuagiua community, Mozambique.

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